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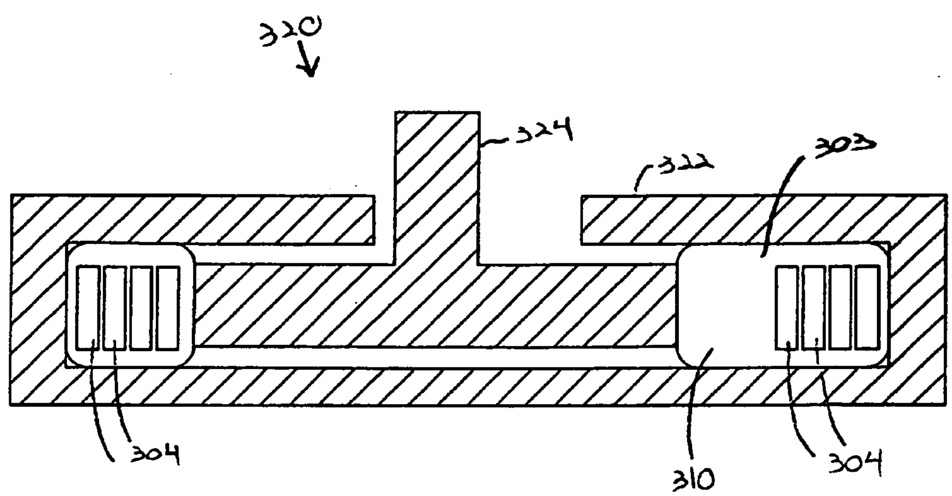

(57) Abstract: A micro-fabricated structure (320) includes a housing (322) defining an actuation chamber (303) with a set of electrodes (304) formed therein. A movable micro-fabricated structure (324) is positioned proximate to the actuation chamber (303). The electrodes (304) cause electrolytic formation of a bubble (310) that produces controlled displacement of the movable micro-fabricated structure (324). The movable micro-fabricated structure (324) may be a flow-controlled, free-standing block valve, a pressure-controlled, free-standing block valve, a free-standing block valve, or a plate (356). In the case of a plate (356), such as a mirror, the plate (356) may be lifted and tilted in a controlled manner. The controlled displacement of the movable micro-fabricated structure (324) may be terminated by evacuating the bubble (310) through a specially shaped escape path, by producing a spark with the electrodes (304), or by electrolytic dissipation of the bubble (310).

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CONTROLLING PHYSICAL MOTION WITH ELECTROLYTICALLY FORMED BUBBLES

This application is a continuation-in-part of U.S. Serial Number 09/309,316, filed May 11, 1999, entitled "Apparatus and Method for Controlling Fluid with an Unattached Micromechanical Block".

BRIEF DESCRIPTION OF THE INVENTION

This invention relates generally to Micro-Electro Mechanical Systems (MEMs). More particularly, this invention relates to a technique for controlling physical motion with electrolytically formed bubbles.

BACKGROUND OF THE INVENTION

Micro-Electro Mechanical Systems (MEMs), which are sometimes called micromechanical devices, micromachines, micro-fabricated structures, or nanostructures are three-dimensional objects that have one or more dimensions ranging from microns to millimeters in size. The devices are generally fabricated utilizing semiconductor processing techniques, such as lithographic technologies.

Standard MEMs actuators are generally ineffective in a fluid environment. For example, electrostatic actuators, such as the elector-static comb drive, will not function with a conducting dielectric, such as water. Actuators, such as thermal bimorph actuators, are of limited value, as the boiling point of the surrounding fluid limits the thermal range of the device. Piezoelectric actuators have been used to some effect in micro-fluid devices. However, these actuators have limited actuation range and are difficult to fabricate.

Thus, it would be highly desirable to provide a fluidic valve with large actuation ranges, which requires minimal energy to generate displacement, which requires little or no energy to maintain displacement, and which requires minimal

energy to return to its initial configuration. Ideally, such a valve could be constructed using standard fabrication techniques.

SUMMARY OF THE INVENTION

A micro-fabricated structure includes a housing defining an actuation chamber with a set of electrodes formed therein. A movable micro-fabricated structure is positioned proximate to the actuation chamber. The electrodes cause the electrolytic formation of a bubble that produces controlled displacement of the movable micro-fabricated structure. The movable micro-fabricated structure maybe a flow-controlled free-standing block valve, a pressure-controlled free-standing block valve, a free-standing block piston, or a plate. In the case of a plate, such as a mirror, the plate may be lifted and tilted in a controlled manner. The controlled displacement of the movable micro-fabricated structure may be terminated by evacuating the bubble through a specially shaped escape path, by producing a spark with the electrodes, or by electrolytic dissipation of the bubble.

The invention provides a fluidic valve with large actuation ranges. The structure of the invention requires minimal energy to generate displacement, requires little or no energy to maintain displacement, and requires minimal energy to return to its initial configuration. Advantageously, the valve is constructed using standard fabrication techniques.

BRIEF DESCRIPTION OF THE DRAWINGS

For a better understanding of the invention, reference should be made to the following detailed description taken in conjunction with the accompanying drawings, in which:

FIGURES 1A-1C illustrate a flow-controlled free-standing block valve in accordance with an embodiment of the invention.

FIGURES 2A-2C illustrates a flow-controlled free-standing block valve in accordance with another embodiment of the invention.

FIGURES 3A-3C illustrate a pressure-controlled free-standing block valve in accordance with an embodiment of the invention.

FIGURES 4A-4H illustrate the operation of a vapor forming mechanism in the form of electrodes, as used in accordance with an embodiment of the invention.

FIGURE 5 illustrates a free-standing block piston in accordance with an embodiment of the invention.

FIGURES 6A-6B illustrate a spring check valve in accordance with an embodiment of the invention.

FIGURE 7 illustrates an extended fluid path controlled by different flow control devices of the invention.

FIGURE 8 illustrates a quartz wafer processed in accordance with an embodiment of the invention.

FIGURE 9 illustrates a silicon-on-insulator wafer processed in accordance with an embodiment of the invention.

FIGURE 10 illustrates a constructed flow control apparatus in accordance with an embodiment of the invention.

FIGURES 11A-11F illustrate the process of fabricating floating silicon blocks from a silicon-on-insulator wafer, in accordance with an embodiment of the invention.

FIGURES 12A-12AA illustrate the process of fabricating electrolysis electrodes that may be used in accordance with an embodiment of the invention.

FIGURES 13A-13S illustrate the process of fabricating a polysilicon heater that may be used in accordance with an embodiment of the invention.

FIGURES 14A-14H illustrate the process of fabricating floating silicon blocks from a silicon on epoxy substrate, in accordance with an embodiment of the invention.

FIGURE 15 illustrates the electrolytic formation of bubbles in accordance with an embodiment of the invention.

FIGURE 16 illustrates the electrolytic formation of a large bubble in accordance with an embodiment of the invention.

FIGURE 17 illustrates a valve operated by the electrolytic formation of bubbles on opposites sides of the valve.

FIGURES 18a-18c illustrate the positional control of a plate using electrolytic bubbles formed in accordance with an embodiment of the invention.

FIGURES 19a-19e illustrate a bubble escape structure formed in accordance with an embodiment of the invention.

Like reference numerals refer to corresponding parts throughout the drawings.

DETAILED DESCRIPTION OF THE INVENTION

Figures 1A-1C illustrate a flow-controlled free-standing block valve 20 constructed in accordance with an embodiment of the invention. The valve 20 operates as a check valve or non-reverse valve, as described below. The valve 20 includes a micromechanical block chamber 21 with a free-standing block 22 positioned within it. Also positioned within the micromechanical block chamber 21 is a block stop 24. The micromechanical block chamber 21, the free-standing block 22, and the block stop 24 are formed within a substrate 27.

As its name implies, the free-standing block 22 is not attached to the substrate 27. Novel processing techniques to release the free-standing block 22 from the substrate 27 are discussed below.

The free-standing block 22 is free to move as viscous forces act upon it. The motion of the free-standing block 22 is constrained by the micromechanical block chamber 21 and the free-standing block 22, as discussed below.

The substrate 27 also defines a fluid path 26. In this embodiment of the invention, the fluid path 26 includes a path into the micromechanical block chamber 21 and a path out of the micromechanical block chamber 21, which is referred to as a flow control port 32. Fluid flowing in the direction of arrow 28 passes through the micromechanical block chamber 21 to reach the other portion of the fluid path 26. That is, the fluid forces the free-standing block 22, in this embodiment a plate structure, against the block stop 24, as shown in Figure 1B, thereby allowing the fluid to pass through the micromechanical block chamber 21 to reach the other portion of the fluid path 26.

Conversely, fluid flowing the direction of arrow 30 is obstructed and limited to the micromechanical block chamber 21, as shown in Figure 1C. That is, Figure 1C illustrates the free-standing block 22 forced against a portion of the micromechanical block chamber 21, thereby preventing fluid from entering the flow control port 32.

The valve 20 of Figures 1A-1C operates to "rectify" fluid flow. In other words, the valve 20 allows more fluid flow in the flow direction 28 for a given force, than in the obstructed direction 30 for an opposite force of the same magnitude. Since

the block 22 is free-standing (i.e., it is released from the substrate 27) there will be a small gap between the block 22 and the substrate 27 and between the overlaying lid (not shown in Figures 1A-1C) and the block 22. Thus, the valve will always experience some leakage under a reverse pressure gradient.

Observe that the free-standing block (e.g., 22 and 42) operates in the same plane as the fluid path 26. As discussed below, semiconductor processing techniques are used to fabricate the valve of the invention. Thus, the valve may have features less than a millimeter, with some embodiments having features of preferably approximately several hundred microns.

The flow-controlled free-standing block valve 40 of Figures 2A-2C corresponds to the apparatus of Figures 1A-1C, except the micromechanical block chamber 41 has an oval shape (instead of the rectangle of Figures 1A-1C), the free-standing block 42 is formed as a cylinder (instead of the plate 22 of Figures 1A-1C), and the block stop 44 has a circular configuration (instead of the square 24 of Figures 1A-1C). Those skilled in the art will appreciate that many other configurations are feasible in view of the structural and processing embodiments disclosed herein.

Figures 3A-3C illustrate a pressure-controlled free-standing block valve 50. Figure 3A illustrates a "t-shaped" free-standing block 52 positioned within a micromechanical block chamber 54. In this embodiment of the invention, the micromechanical block chamber 54 forms a pressure chamber. A fluid path 56 is also shown in Figures 3A. The free-standing block 52, micromechanical block chamber 54, and fluid path 56 are formed in a substrate 58.

Figure 3B illustrates a valve opening high pressure region 60, which forces the free-standing block 52 into a retracted position. Figures 3C illustrates a valve closing high pressure region 62, which forces the free-standing block 52 into an extended or closed position. The high pressure regions are formed with vapor forming mechanisms fabricated at the location of the high pressure regions. For example, the vapor forming mechanism may be a heater that operates to vaporize fluid and thereby creates a high pressure region that moves the free-standing block 52. Alternately, electrodes may be used to electrolytically form a high pressure region in the form of bubbles that move the free-standing block 52.

Figures 4A-4H illustrate the operation of electrolytically forming bubbles in accordance with an embodiment of the invention. Figure 4A illustrates a fluid 64, for example water, with a set of electrodes 65 positioned therein. A voltage potential is applied between the electrodes 65. As a result, an electrochemical reaction occurs, evolving hydrogen at one electrode and oxygen at the other electrode. These gases form micro-bubbles 66, as shown in Figure 4B. The micro-bubbles 66 grow and join, as shown in Figures 4C. Ultimately, a large bubble 67 forms, as shown in Figure 4D. The large bubble 67 contains a stoichiometric mixture of hydrogen and oxygen. Observe in Figure 4D that the large bubble 67 displaces the fluid 64, such that it appears that there is more fluid 64 in Figure 4D than in Figure 4A. The large bubble 67 may be eliminated by applying an additional potential across the electrodes 65, so as to form a spark 68, as shown in Figure 4E. The spark 68 causes the hydrogen and oxygen gases to form water, thus collapsing the bubble. Figure 4F shows the collapsing of the bubble 67, while Figure 4G illustrates the downward fluid pressure resulting from the collapsed bubble. Finally, Figure 4H illustrates a steady state condition corresponding to Figure 4A.

The foregoing electrolysis process is isothermal; that is, no energy is lost to heat transfer. Unlike thermal bubbles, electrolysis bubbles will exist indefinitely until combusted with a spark. When combusted, the electrolysis gasses disappear in a faction of a second. The pressures generated inside electrolysis bubbles create much larger actuation forces than electrostatic forces created with reasonable voltages. Thus, micro bubbles formed through electrolysis are a quick, efficient, and effective method of actuation of the block valve of the invention.

Figure 5 illustrates a free-standing block piston 70 in accordance with another embodiment of the invention. The piston 70 includes a free-standing block 72 positioned within a micromechanical block chamber 74. The free-standing block 72 and the micromechanical block chamber 74 are formed in a substrate 76. The micromechanical block chamber 74 includes a controlled fluid port 78, which is used to store fluid from a fluid path 26 and to eject water into the fluid path 26 when the free-standing block 72 is actuated. A vapor forming mechanism, such as a heater 80 or electrodes, is used to move the free-standing block 72. Ideally, the free-standing block 72 maintains separation between a fluid in the fluid path 26 and a fluid in the

micromechanical block chamber 74, while allowing their pressures to equalize. This is useful for fluids that cannot be mixed, but must act upon one another. An example of this is the use of thermal actuation to move insulin. Insulin is destroyed when it is boiled. The piston 70 allows boiling of a fluid in the micromechanical block chamber 74, to move the free-standing block 72 and thereby move insulin in the path 26, without damaging the insulin.

Figures 6A and 6B illustrate a spring check valve 90 implemented in accordance with another embodiment of the invention. The figures show micromechanical springs 92 attached to a micromechanical paddles 94. In a resting position, the micromechanical paddles 94 rest against a paddle support 96. Arrow 98 illustrates a flow direction, while arrow 100 illustrates an obstructed direction. While the paddles 94 in this embodiment are free-standing, the paddles 94 are connected to a structure that is secured to the rest of the substrate. Thus, unlike the previous embodiments of the invention, a completely free-standing valve structure does not exist in this embodiment. However, it should be observed that if a weak spring is fabricated, its mechanical characteristics will correspond to the mechanical characteristics of the embodiments of the invention utilizing a completely free-standing valve structure. Thus, in this instance a block valve is formed with a weak spring.

The apparatus of Figures 6A and 6B was implemented with a 60 micro-meter channel width 106. The valve was fabricated on a silicon-on-insulator wafer substrate. The paddles 94 were 90 microns and the coiled springs 92 were 355 microns. The total footprint of the device was 100 microns by 200 microns.

Figure 7 illustrates that different devices of the invention can be combined to control an extended fluid path 110. In Figure 7, an extended fluid path 110 is controlled by flow-controlled free-standing block valves 20A and 20B, pressure-controlled free-standing block valves 50A and 50B, and free-standing block piston 70.

The structures of different embodiments of the invention have now been described. Attention presently turns to a discussion of different ways of fabricating the devices of the invention. General fabrication steps are initially discussed. Thereafter, more detailed fabrication steps are disclosed.

The device of the invention may be constructed with two wafers: one quartz and one silicon. The electrical components, such as wires and heaters, may be fabricated on the quartz wafer using a four mask process. Quartz is useful because it is stable at temperatures in excess of 1000°C and is therefore compatible with polysilicon depositions and anneals, while being transparent, thus, allowing one to visualize flow in the channels. Channels, fluidic interconnects, and fluidic components are etched into a silicon wafer using a multiple mask process. The silicon wafer may be a Silicon on Insulator (SOI) wafer, which has a thin oxide layer buried between 20 and 100 microns below the surface of the wafer. SOI wafers allow one to create released, movable structures, such as valves, while also providing a buried etch-stop that allows more precise control over the depth of fluid channels.

The two dice are bonded using a patterned polymer "gasket" layer, and attached and wire bonded to a copper printed circuit board. Finally, a tubing structure is glued to the silicon dice, thereby completing the fluidic interconnects. This general overview of the fabrication of the device will be supplemented with the following detailed description.

The fabrication process for the quartz cover plate may be implemented with a four mask process. First, shallow grooves are etched into the quartz wafer, forming troughs into which wires and heaters can be placed (Mask 1). Etching these grooves keeps the tops of heaters and wires below the level of the wafer surface, thus providing a better surface for subsequent bonding. A plasma may be used to etch the quartz. Alternately, a hydrofluoric acid etch may be used.

Approximately 3000Å of doped polysilicon is then deposited using Low Pressure Chemical Vapor Deposition (LPCVD). This layer is then annealed at 9500° C for one hour. The precise thickness of the layer is adjusted before each run to achieve a layer with a resistance of approximately 25 Ohms.

The polysilicon layer is then patterned (Mask 2) to form heaters using wet silicon etchant. After a dip in Hydrofluoric acid, approximately one-half micron of Aluminum/2% silicon is then sputtered onto the wafer, patterned (Mask 3), and etched using wet aluminum etchant. The wafers are then manually wiped clean to remove the final monolayer of 2% silicon. Finally, a thin layer of approximately one-half micron of Low Temperature Oxide (LTO) is then deposited using LPCVD at 400°C. This

layer forms a passivation layer which prevents electrical components from coming into contact with fluid.

Electrical bond pads are formed by etching vias through this layer with a plasma, stopping on the aluminum layer (Mask 4). Figure 8 illustrates the completed quartz substrate. In particular, Figure 8 illustrates a quartz wafer 120 with wires 122 formed thereon. Heaters 124 are also formed on the quartz wafer 120. Figure 8 also illustrates bonding pads 126, and aluminum layer 130, a doped region 132, and the Low Temperature Oxide 134.

There are several commonly encountered fabrication problems which can be addressed with appropriate design. First, when looking through the wafer from the back side, the aluminum layer appears much brighter than other layers, thereby making visualization difficult. Second, in operation, the polysilicon heaters can easily become hotter than the melting point of the silicon wires, thereby making the electrical connection between the aluminum layer and polysilicon layer prone to failure. Third, fabrication errors in the aluminum layer can create gaps in the aluminum wires, making the connected components useless. All three of these problems were addressed in later fabrication runs by extending the polysilicon layer under nearly all of the aluminum layer. All wires consist of wide polysilicon components with a slightly narrower aluminum component on top. This design decreases apparent brightness of the aluminum layer, ensures good contact between polysilicon and aluminum layers, and provides a fail-safe against small gaps in the aluminum wires.

Around the bond pads, other problems necessitate a different strategy. Here, the main concern is that both the polysilicon and aluminum layers (or the aluminum bond wires) will simultaneously come into contact with fluid during the assembly process. If this occurs, the elecrochemical reactions will cause a rapid degradation of the aluminum layer. To prevent this, in the area of the bond pads the aluminum layer should overlap the polysilicon layer completely, and vias through the LTO passivation layer should not open up connections to the polysilicon layer.

Fabrication of the silicon wafer, which contains the fluid channels, valve structures, and fluid interconnects, may be implemented with two mask steps. Typically, a Silicon-On- Insulator (SOI) wafer, containing a thin buried oxide layer is used, as the buried oxide layer serves as an etch stop when etching the fluid channels,

and can also be etched away to form released, movable structures. By way of example, the fabrication runs were conducted using SOI wafers with a 525 microns silicon "handle" layer, a one-half micron "buried" oxide layer, and a 25 micron silicon "process" layer.

The wafer is preferably marked for front-side-back-side alignment targets. Through-holes are patterned (Mask 5) on the back side of the wafer using approximately eight microns of photoresist, which is then etched to the buried oxide layer. The photoresist is then stripped, the wafer cleaned, and a brief wet hydrofluoric acid etch is performed to remove the buried oxide layer. The channel/valve pattern is then applied to the front side of the wafer (Mask 6), the wafer is photoresist-bonded to a handle wafer, and then the channel/valve pattern is etched 25 microns, again stopping on the buried oxide layer.

The photoresist is then stripped, the handle wafers removed, and the wafers rinsed, but not dried. Drying the wafers can easily destroy any fragile valve structures. A thick layer of photoresist is applied while slowly spinning the wet wafers. The wafer is then diced, using the thick photoresist layer to protect the valve structures. The photoresist is then stripped using acetone, the dice are rinsed in isopropyl alcohol and de-ionized water, and they are then HF etched to release the valve structures. The finished dice are then gently dried using a heat lamp or microscope light.

A diagram of the completed die is shown in Figure 9. Figure 9 illustrates an SOI wafer 140 with fluid interconnects 142 formed therein. The figure also illustrates a buried oxide layer 144, channel walls 146, and released valves 148.

The two substrates are assembled as follows. First, a layer of negative photoresist is applied to the quartz die and patterned (Mask 7), forming an "O-Ring" type seal around each of the fluid channels. The quartz and silicon dice are then aligned, pressed together, and heated to about 160°C using a flip-chip bonding system, thereby reflowing the negative photoresist and forming sealed fluid channels. The device is then placed on a small section of dicing tape (quartz down), and epoxy is pushed up along two sides of the dice (the sides without electrical connectors), forming a stronger mechanical bond. After the epoxy hardens, the dicing tape is pealed away, leaving small tabs of epoxy on two ends.

This two-dice sandwich is then epoxy mounted to a two-sided copper printed circuit board using the epoxy tabs as handles. The dice are mounted quartz side down, so that the electrical bond-pads on the quartz die, and the fluidic interconnects on the silicon die, both face up. Fluid within the device is visualized by looking up through a hole in the PC Board, and into the device. Aluminum wire-bonds are then made between the bond-pads on the quartz die and the copper traces on the PC board, and the wirebonds are encased in epoxy.

Next, fluidic interconnects are formed by gluing one inch Polyimide tubes into the interconnect holes on the silicon die using JB Weld brand engine-block epoxy. Once glued in place, polyethylene tubing and Luer fittings are attached to the Polyimide tubes using small sections of heat-shrink tubing. Finally, magnetic tape is applied to the PC board to mount the device to the probe station during testing. The PC board may be connected to electrical components using edge board connectors, and the fluidic connectors may be attached to syringes, valves, or tubing, as desired, using standard Luer fittings.

The assembled device is shown in Figure 10. Figure 10 illustrates an SOI wafer 140. The weld 152 supports the tubing 154 positioned in the fluid interconnects 142. A gasket layer 156 is positioned between the SOI wafer 140 and the quartz wafer 120. Figure 10 also illustrates the wire bonds 160 and PC board 162.

Figures 11A-11F illustrate a process for fabricating floating silicon blocks from a Silicon-On-Insulator (SOI) wafer, in accordance with an embodiment of the invention. An overview of the process is as follows. The shape of the fluid chambers and channels are defined using standard lithographic techniques. Vertical walled trenches are etched down to the oxide insulator layer. The wafer is submerged in hydrofloric acid to free the structures with narrow cross-sections. A cover plate is fabricated with heaters or electrolysis electrodes as well as electrical and fluid connections. The polysilicon heaters are fabricated with normal lithographic techniques. Platinum electrodes are fabricated using a lift-off process. Individual wafers are then bonded together.

Figure 11A illustrates a Silicon-On-Insulator (SOI) wafer including a single crystal silicon etch layer 180, a silicon dioxide layer 182, and a single crystal silicon handle layer 184. Photoresist is spun onto the wafer, resulting in a photoresist layer

186, as shown in Figure 11B. The photoresist 186 is subsequently processed by conventional techniques to produce a patterned photoresist 187, as shown in Figure 11C. The patterned photoresist corresponds to the shape of the micromechanical block chamber, free-standing block, fluid path and other components that are to be fabricated. Deep reactive ion etching (DRIE) is then used to produce deep trenches 188, as shown in Figure 11D. The patterned photoresist 187 is then stripped, resulting in the structure of Figure 11E. The silicon dioxide 182 is then etched, resulting in the device of Figure 11F. Figure 11F illustrates a micromechanical block chamber 21, a block stop 24, and a free-standing block 22.

Figures 12A-12AA illustrate a process for forming platinum lift-off electrolysis electrodes in accordance with an embodiment of the invention. Figure 12A illustrates a wafer of single crystal silicon 180. An insulating layer of nitride 190 is grown onto the wafer 180, resulting in the structure of Figure 12B. Polysilicon 192 is then deposited, resulting in the structure of Figure 12C. Photoresist 186 is then spun onto the wafer, resulting in the structure of Figure 12D. Conventional masking techniques are then utilized to produce a patterned photoresist 187 defining electrode structures, as shown in Figure 12E. The polysilicon layer 192 is then etched to form an etched polysilicon layer 194, as shown in Figure 12F. The patterned photoresist 187 is then removed, resulting in the device of Figure 12G. A thermally grown silicon dioxide layer 182 is then formed, as shown in Figure 12H. Photoresist 186 is placed on the silicon dioxide layer 182, as shown in Figure 12I. A contact mask pattern is used to produce a patterned photoresist 187 defining contacts, as shown in Figure 12J. The silicon dioxide is then etched to produce an etched silicon dioxide layer 196, as shown in Figure 12K. The photoresist 187 is then removed to produce the device of Figure 12L.

A thick layer of photoresist 189 is then spun onto the device, producing the device of Figure 12M. A plantinum mask is then utilized to produce a corresponding patterned thick photoresist 200, as shown in Figure 12N. Titanium 202 is then sputtered onto the device, resulting in the structure of Figure 12O. Platinum 204 is then sputtered onto the device, resulting in the structure of Figure 12P. The next processing step is to strip the photoresist, thereby lifting off the platinum and titanium

to produce the device of Figure 12Q, which shows patterned platinum 205. Aluminum 206 is then sputtered onto the device, resulting in the structure of Figure 12R.

Photoresist 186 is then spun onto the device to produce the structure of Figure 12S. The photoresist is then patterned with a mask to produce patterned photoresist 187 defining aluminum regions. This is shown in Figure 12T. The unmasked aluminum 206 is then etched to produce the device of Figure 12U. Subsequently, the photoresist is stripped to produce the device of Figure 12V. Photoresist 186 is then spun onto the device to produce the device of Figure 12W. The photoresist is patterned with an insulating mask to produce the device of Figure 12X. Negative photoresist 210 is then spun onto the device, resulting in the structure of Figure 12Y. A gasket mask is then patterned to produce patterned negative photoresist, as shown in Figure 12Z. The processed SOI wafer 214 of Figure 11F is then attached, as shown in Figure 12AA.

Figures 13A-13S illustrate processing steps to fabricate a polysilicon heater. A single crystal silicon wafer 180 is initially provided, as shown in Figure 13A. A silicon nitride insulating layer 190 is deposited onto the wafer 180 to produce the device of Figure 13B. Polysilicon 192 is then deposited to produce the device of Figure 13C. Photoresist 186 is then spun onto the device to produce the structure of Figure 13D. A heater mask photoresist pattern 187 is then formed, as shown in Figure 13E. The polysilicon 194 is then etched to produce the device of Figure 13F. The photoresist 187 is then stripped, yielding the device of Figure 13G. Aluminum 206 is then sputtered onto the device to produce the structure of Figure 13H. Photoresist 186 is then spun onto the wafer to produce the device of Figure 13I. The photoresist 186 is processed to produce a patterned photoresist 187 to operate as an aluminum mask, as shown in Figure 13J. The unmasked aluminum is then etched to produce etched aluminum 208, as shown in Figure 13K. The photoresist 187 is then stripped to produce the structure of Figure 13L.

Low temperature silicon dioxide is then deposited, as shown with layer 182 of Figure 13M. A patterned photoresist 187 is then applied to the device to produce the structure of Figure 13N. The silicon dioxide 182 is then etched to produce etched silicon dioxide 216, as shown in Figure 13O. The photoresist 187 is then stripped to produce the device of Figure 13P. Negative photoresist 210 is then applied to the

device, as shown in Figure 13Q. Patterned negative photoresist 212 is formed for use as a gasket mask, as shown in Figure 13R. The SOI wafer 214 of Figure 11F is then attached, as shown in Figure 13S.

Figures 14A-14H illustrate a silicon-on-epoxy process in accordance with an embodiment of the invention. A single crystal silicon wafer 180 (e.g., 100 microns thick) is shown in Figure 14A. Photoresist is spun onto the wafer and baked to produce the device 218 of Figure 14B. Figure 14C shows a silicon wafer 220 prepared with heaters or platinum electrodes using one of the previously described processes. Epoxy 222 is then spun onto the device to produce the structure of Figure 14D. The device 218 of Figure 14B is then attached via the epoxy 222, as shown in Figure 14E. Patterns for the valves and channels are defined on the top of the wafer 218, as shown in Figure 14F. The valves and channels may be aligned to the features on the wafer 220 using infrared light. Deep reactive ion etching is then used to produce etch trenches 230, as shown in Figure 14G. The features may then be released with an oxygen plasma to produce the structure of Figure 14H. Figure 14H illustrates a free-standing block 22 positioned within a micromechanical block chamber 21. Figure 14H also illustrates etched epoxy 222 supporting the original substrate 180. A cover plate is then attached over the structure, as previously disclosed.

Those skilled in the art will appreciate that the foregoing processing steps may be used to fabricate a variety of devices. Figure 15 is an example of such a device. Figure 15 illustrates an apparatus 300 for controlling the physical motion of a micro-fabricated structure using electrolytically formed bubbles. In particular, Figure 15 illustrates a micro-fabricated housing 302 defining an actuation chamber 303 with a set of electrodes 304 formed therein. The housing 302 encloses water or an aqueous solution. The electrodes are activated by applying a current to them. This results in the generation of a set of small bubbles 306. The bubbles grow until they expel fluid through the gaps between the housing 302 and the micro-fabricated piston 308.

Figure 16 corresponds to Figure 15, but illustrates a single large bubble 310 formed from the small bubbles 306 after the electrodes are activated for a period of time. Surface tension keeps the bubble 310 inside the chamber and allows it to push the piston 308 in a controlled manner. This bubble formation sequence corresponds to the bubble formation sequence described in connection with Figures 4A-4D.

Observe in Figure 16 that the single large bubble 310 covers the electrodes 304. This causes the electrolytic reaction to cease. This feature of the invention can be used for self-limiting control of the electrolysis process. If ongoing electrolysis is desired, then the chamber 303 can be constructed to include a converging passage which the bubble 310 will not enter. Electrodes can then be placed in the converging passage to insure ongoing electrolysis.

When current is removed from the electrodes 304, the oxygen and hydrogen gasses which make up the bubble react with each other on the catalytic surface (e.g., platinum) of the electrodes 304 and the bubble shrinks. A device, such as a second bubble chamber can force the piston in the opposite direction, as shown in connection with Figure 17. A spring may also operate as a restoring force. U.S. Serial Number 09/451,621, filed November 19, 1999, entitled "Apparatus and Method for Regulating Fluid Flow with a Micro-Electro Mechanical Block" discloses a spring structure that may be used in connection with the invention. The cited application is incorporated by reference herein.

Those skilled in the art will recognize a number of advantages associated with the structure of Figures 15-16. The device facilitates large actuation ranges in an aqueous environment using very little power. The small scale of the device exploits surface tension effects, which become more important as size decreases. The use of electrolysis generated bubbles instead of thermally generated bubbles reduces the power consumption of the device.

The technique of the invention is useful to actuate microscopic devices, such as pumps and valves in micro-fluidic systems where the working fluid is an aqueous solution. Bubbles can be used in fluid environments where other micro-actuators, such as electrostatic actuators are not feasible. The electrolysis bubbles use more than 4 orders of magnitude less power than thermal actuators or thermally generated micro-bubbles. This performance enhancement is largely attributable to the fact that once a bubble is formed, little or no additional energy is required to maintain the bubble.

Figure 17 illustrates an alternate apparatus 320 for controlling the physical motion of a structure using electrolytically formed bubbles. The apparatus 320 of Figure 17 includes a micro-fabricated housing 322 and an associated micro-fabricated structure (e.g., a valve) 324. Figure 17 also illustrates electrodes 304. The electrodes

304 on the right-side of the figure have been activated to form a large bubble 310 in actuation chamber 303; the bubble 310 displaces the valve 324 to the left-side of the figure. By activating the electrodes on the left-side of the figure, the valve 324 is displaced to the right-side of the figure.

The electrolytic bubble forming techniques of the invention may be used in connection with other devices. Figures 18A-18C illustrate an exemplary device 350. The device 350 of Figure 18A includes micro-fabricated anchors 352 connected to micro-fabricated tethers 354. In turn, the tethers 354 are connected to a micro-fabricated plate (e.g., a polysilicon mirror) 356. Electrodes are formed beneath the plate 356. When activated, the electrodes form small bubbles, causing the plate 356 to be displaced, as shown in Figure 18B. Eventually, a large bubble is formed, producing a larger displacement, as shown in Figure 18C. The bubble can be formed to either lift the plate 356 vertically or to simultaneously lift and tilt the plate 356 in a predetermined manner.

The large bubbles formed in connection with the embodiments of Figures 15-18 may be eliminated by applying additional power to the electrodes, which causes a spark and the collapse of the bubble, as discussed in connection with Figures 4E-4H. Alternately, the bubble may be eliminated by applying a reverse polarity current to the electrodes which will cause a reverse electrolytic reaction to shrink the bubble.

Figures 19A-19E illustrate an alternate technique for collapsing an electrolytically formed bubble of the invention. Figure 19A illustrates a bubble 402 formed in an actuation chamber 403. The bubble 402 is used to move a block 404. Figure 19A also illustrates an evacuation path 406 that is used once the block 404 is displaced.

Figure 19B illustrates the bubble 402 in a larger configuration, causing the displacement of the block 404. In Figure 19C it can be seen that the bubble 402 has pushed the block 404 so as to allow access to the evacuation path 406. The cross-sectional area at the base of the evacuation path 406 is larger than the cross-sectional area of the actuation chamber 403. Thus, the bubble enters the evacuation path 406.

Figure 19D illustrates that the pressure differential between the actuation chamber 403 and the evacuation path 406 pushes the bubble out of the actuation chamber 403 and into the evacuation path 406. The growing cross-sectional area of

the evacuation path 406 facilitates this transfer of the bubble from the actuation chamber 403 to the evacuation path 406. Figure 19E illustrates the bubble 402 being completely evacuated into the evacuation path 406.

Observe that the bubble expands until the base of the bubble evacuation path 406 is wider than the actuation chamber 403. At that point, the radius of curvature of the bubble in the evacuation path 406 is greater than in its radius of curvature in the actuation chamber 403. The pressure drop across the gas liquid interface is inversely proportional to the radius of curvature. Thus, since the pressure inside the actuation chamber 403 is greater than in the evacuation path, the bubble is pushed out of the actuation chamber.

The technique disclosed in connection with Figure 19 relies upon controlling the radius of curvature of the bubble. A variety of alternate techniques may be used to control the radius of curvature of the bubble so that the bubble moves from the actuation chamber 403 to the evacuation path 406. For example, hydrophobic and hydrophilic surfaces may be used to control the radius of curvature of the bubble. In addition, chemical concentration gradients and thermal gradients may be used to control the radius of curvature of the bubble.

Observe that the invention does not require a perfectly sealed membrane. Since most biological fluids are aqueous solutions, this invention can use those fluids as working fluids, whereas a device which uses a specific solution would have to be separated from those fluids by a membrane. Since this invention does not require a sealed membrane, it is easier to fabricate.

The foregoing description, for purposes of explanation, used specific nomenclature to provide a thorough understanding of the invention. However, it will be apparent to one skilled in the art that the specific details are not required in order to practice the invention. In other instances, well known circuits and devices are shown in block diagram form in order to avoid unnecessary distraction from the underlying invention. Thus, the foregoing descriptions of specific embodiments of the present invention are presented for purposes of illustration and description. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed, obviously many modifications and variations are possible in view of the above teachings. The embodiments were chosen and described in order to best explain the

principles of the invention and its practical applications, to thereby enable others skilled in the art to best utilize the invention and various embodiments with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the following claims and their equivalents.

IN THE CLAIMS:

1. A method of controlling the physical motion of a micro-fabricated structure, said method comprising the steps of:

forming a bubble electrolytically; and

applying said bubble to a micro-fabricated structure to produce controlled motion of said micro-fabricated structure.

2. The method of claim 1 wherein said forming step includes the step of applying current to at least one electrode to form said bubble.

3. The method of claim 1 wherein said applying step includes the step of applying said bubble to a micro-fabricated structure selected from the group comprising: a flow-controlled free-standing block valve, a pressure-controlled free-standing block valve, and a free-standing block piston.

4. The method of claim 1 wherein said applying step includes the step of applying said bubble to a plate.

5. The method of claim 4 wherein said applying step includes the step of applying said bubble to a plate with a mirrored surface.

6. The method of claim 4 wherein said applying step includes the step of applying said bubble to a plate to produce controlled vertical displacement of said plate while said plate remains in an initial planar orientation.

7. The method of claim 4 wherein said applying step includes the step of applying said bubble to a plate to produce controlled vertical displacement of said plate accompanied by a controlled tilt of said plate from an initial planar orientation.

8. The method of claim 1 further comprising the step of collapsing said bubble with a spark.

9. The method of claim 1 further comprising the step of shrinking said bubble with a reverse electrolytic reaction.

10. The method of claim 1 wherein said forming step includes the step of forming said bubble electrolytically within an actuation chamber, said method further comprising the step of exposing said bubble to an evacuation path with a first cross-sectional area larger than the cross-sectional area of said actuation chamber, thereby allowing said bubble to enter said evacuation path.

11. The method of claim 10 wherein said exposing step further comprises the step of exposing said bubble to an evacuation path with a second cross-sectional connected to said first cross-sectional area, said second cross-sectional area being larger than said first cross-sectional area, thereby routing said bubble from first cross-sectional area to said second cross-sectional area and thereby transferring said bubble from said actuation chamber to said evacuation path.

12. The method of claim 1 wherein said forming step includes the step of forming said bubble electrolytically within an actuation chamber, said method further comprising the step of exposing said bubble to an evacuation path configured to alter the radius of curvature of said bubble in such a manner as to facilitate transfer of said bubble from said actuation chamber to said evacuation path.

13. A micro-fabricated structure, comprising:

a housing defining an actuation region with at least one electrode formed therein; and

a movable micro-fabricated structure positioned proximate to said actuation region;

wherein said electrodes cause the electrolytic formation of a bubble that produces controlled displacement of said movable micro-fabricated structure.

14. The micro-fabricated structure of claim 13 wherein said at least one electrode processes a current to cause the electrolytic formation of said bubble.

15. The micro-fabricated structure of claim 13 wherein said movable micro-fabricated structure is selected from the group comprising: a flow-controlled free-standing block valve, a pressure-controlled free-standing block valve, and a free-standing block piston.

16. The micro-fabricated structure of claim 13 wherein said movable micro-fabricated structure is a plate.

17. The micro-fabricated structure of claim 16 wherein said movable micro-fabricated structure is a plate with a mirrored surface.

18. The micro-fabricated structure of claim 16 wherein said electrodes are adapted to produce controlled vertical displacement of said plate while said plate remains in an initial planar orientation.

19. The micro-fabricated structure of claim 16 wherein said electrodes are adapted to produce controlled vertical displacement of said plate accompanied by controlled tilt of said plate from an initial planar orientation.

20. The micro-fabricated structure of claim 13 wherein said at least one electrode produces a spark to collapse said bubble.

21. The micro-fabricated structure of claim 13 wherein said at least one electrode is operated to produce a reverse electrolytic reaction to shrink said bubble.

22. The micro-fabricated structure of claim 13 further comprising an evacuation path with a first cross-sectional area larger than the cross-sectional area of said actuation region, thereby allowing said bubble to enter said evacuation path.

23. The micro-fabricated structure of claim 22 wherein said evacuation path further comprises a second cross-sectional area larger than said first cross-sectional area, thereby routing said bubble from first cross-sectional area to said second cross-

sectional area and thereby transferring said bubble from said actuation region to said evacuation path.

24. The micro-fabricated structure of claim 13 further comprising an evacuation path configured to alter the radius of curvature of said bubble in such a manner as to facilitate transfer of said bubble from said actuation region to said evacuation path.

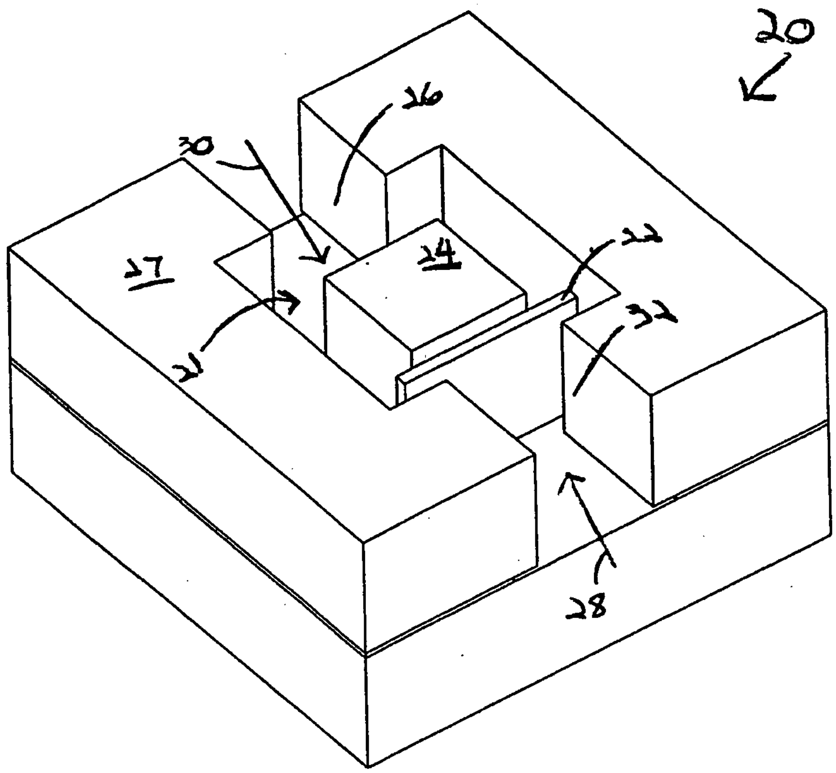


Fig. 1A

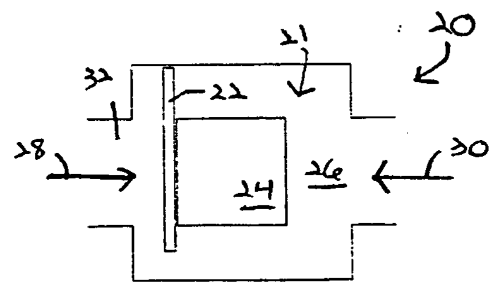


Fig. 1B

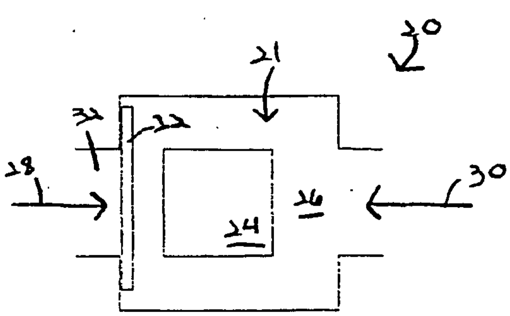


Fig. 1C

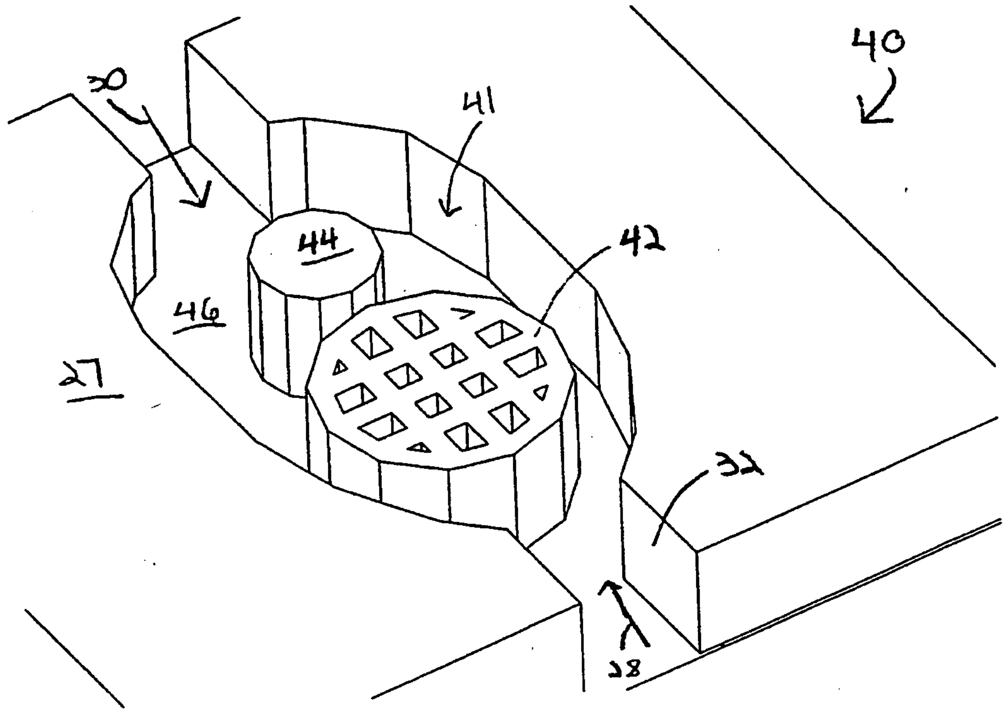


Fig. 2A

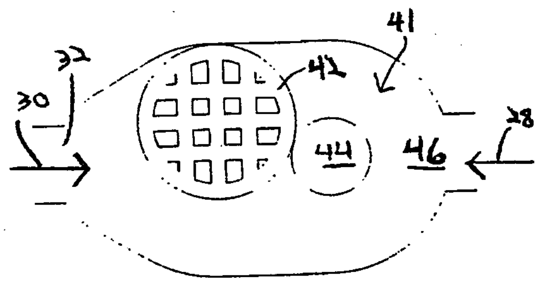


Fig. 2B

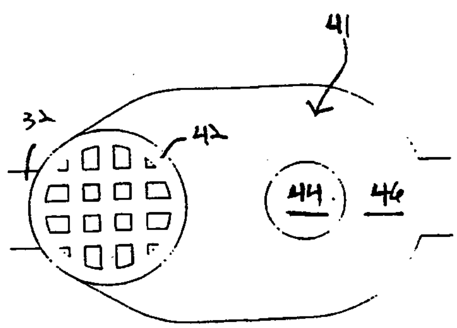


Fig. 2C

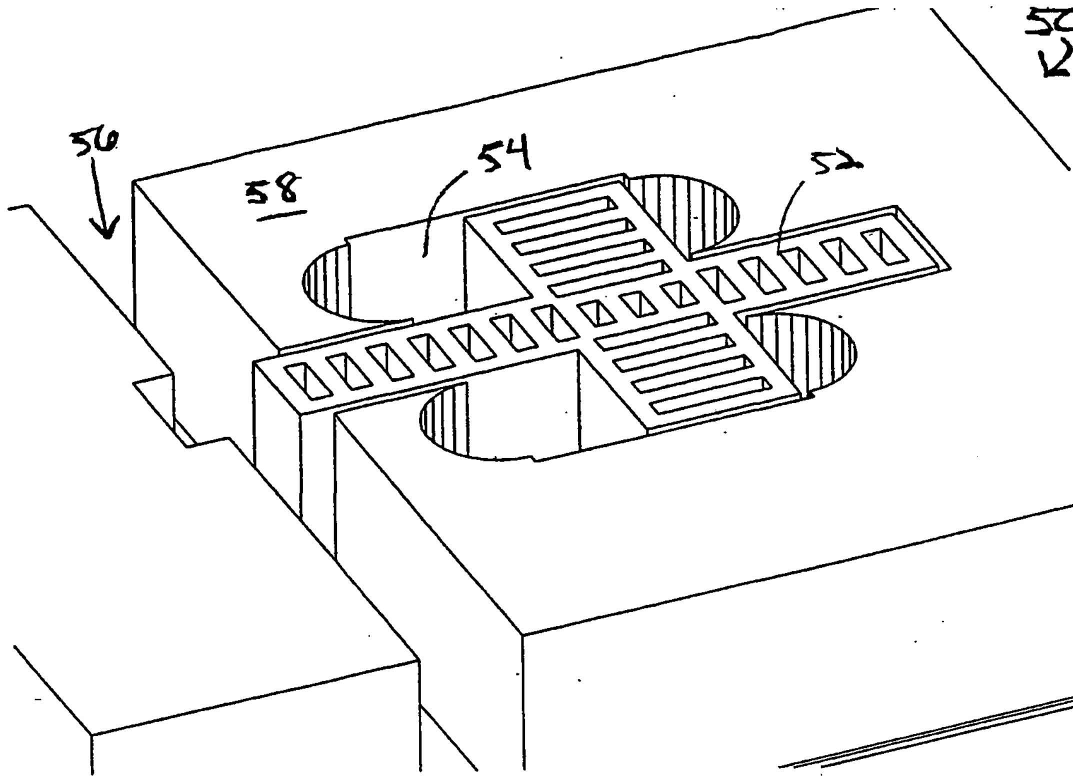


Fig. 3A

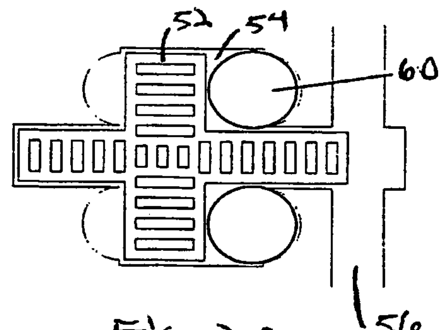


Fig. 3B

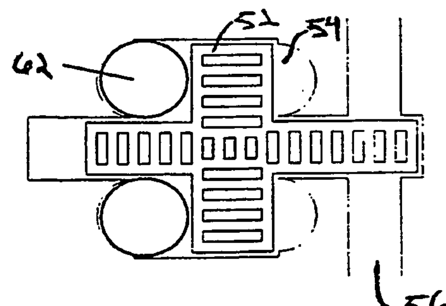


Fig. 3C

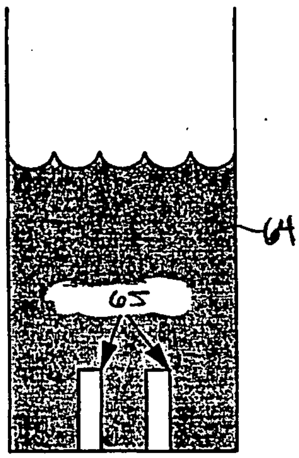


Fig. 4A

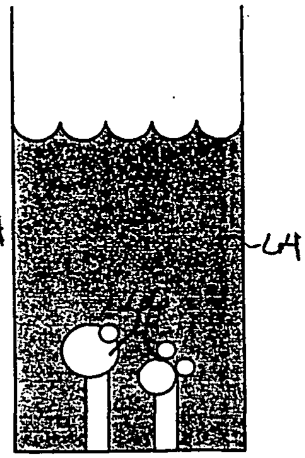


Fig. 4B

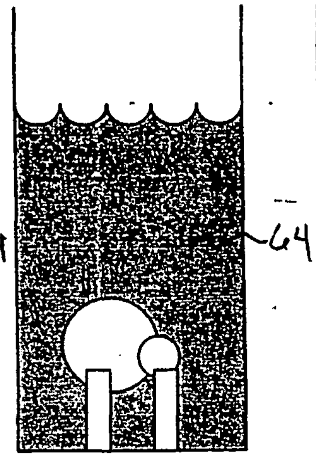


Fig. 4C

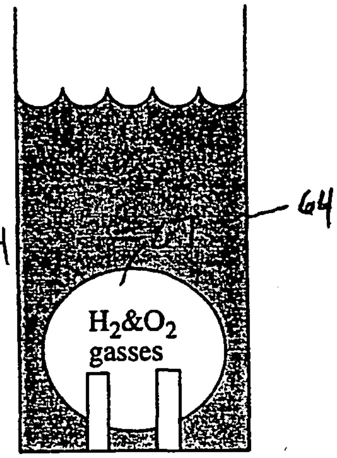


Fig. 4D

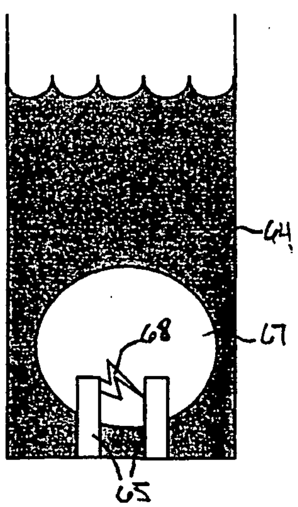


Fig. 4E

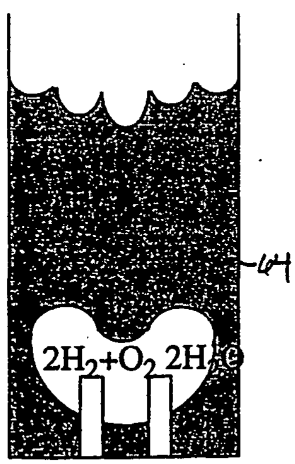


Fig. 4F

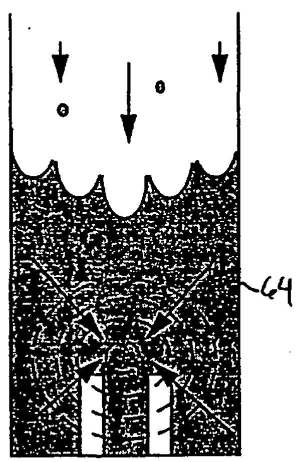


Fig. 4G

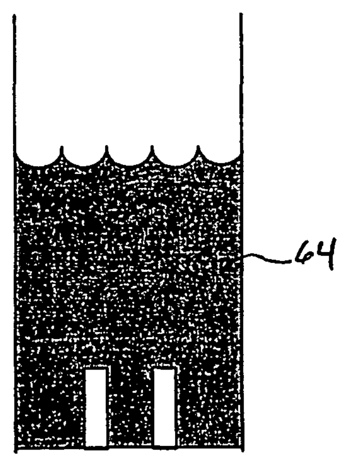


Fig. 4H

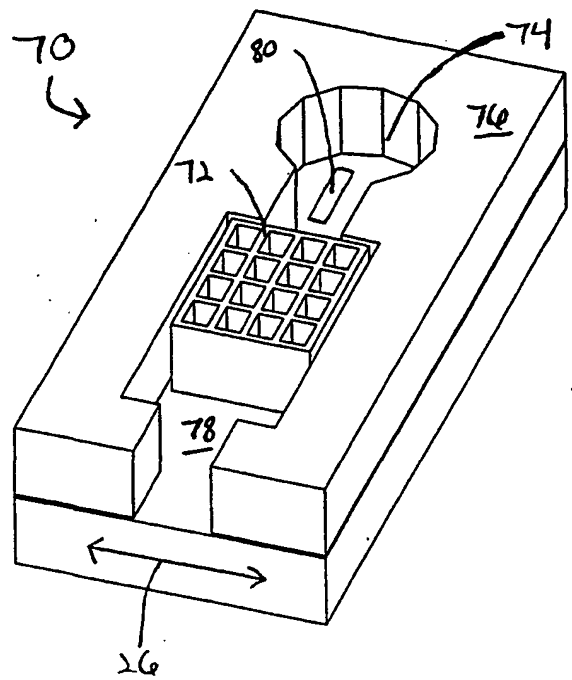


Fig. 5

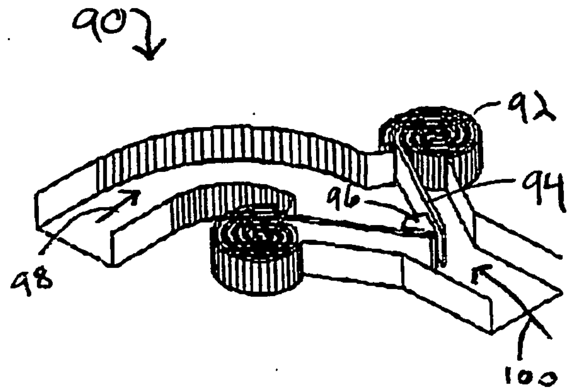


Fig. 6A

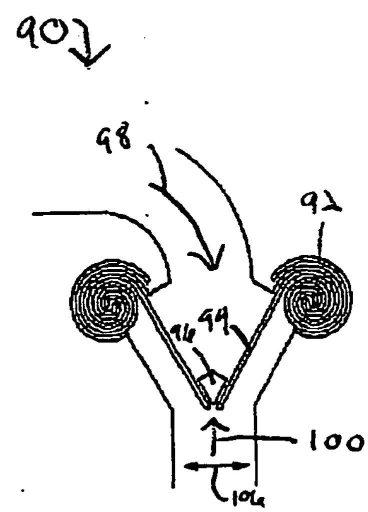


Fig. 6B

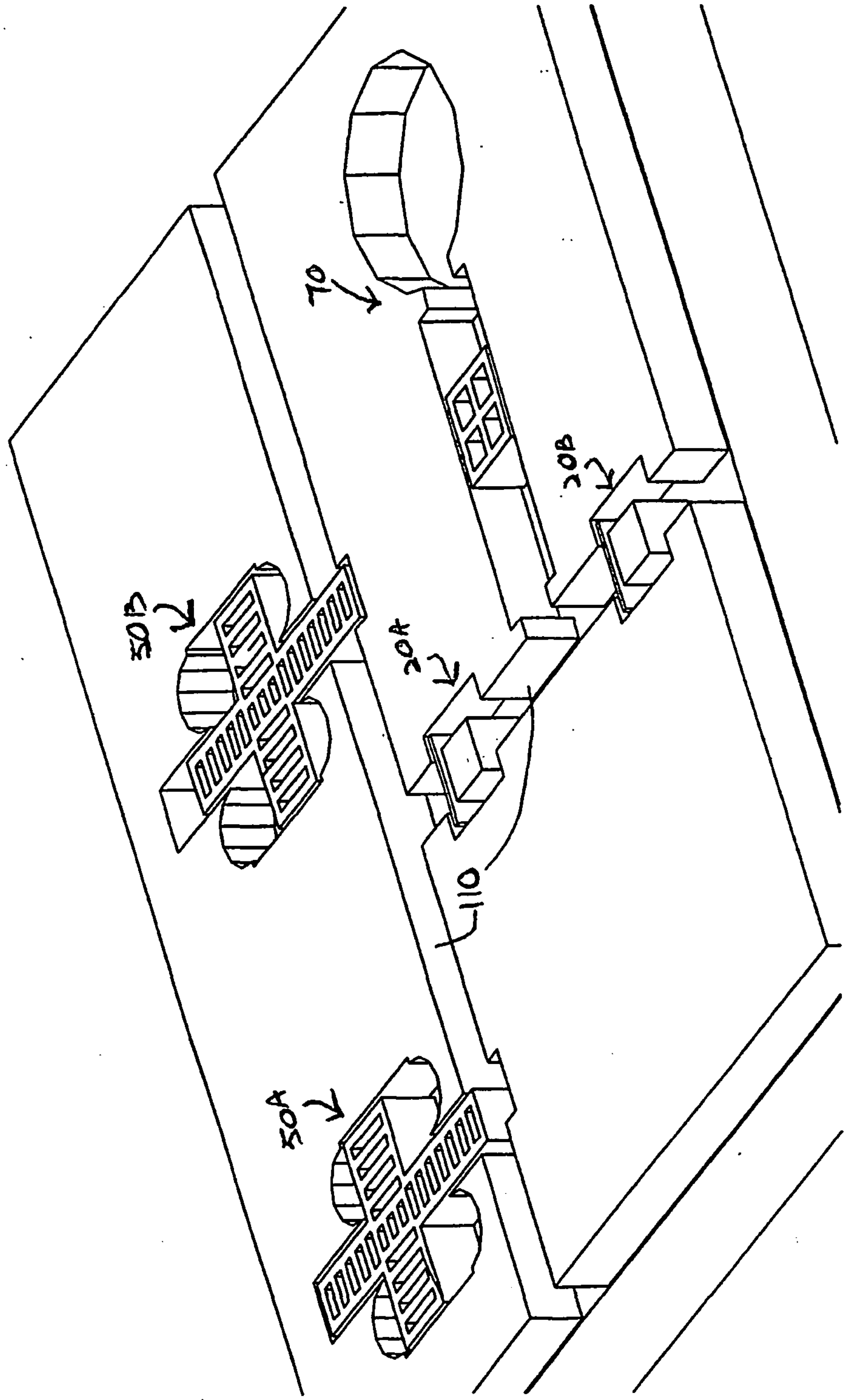


Fig. 7

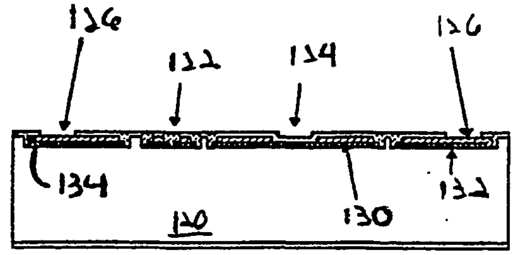


Fig. 8

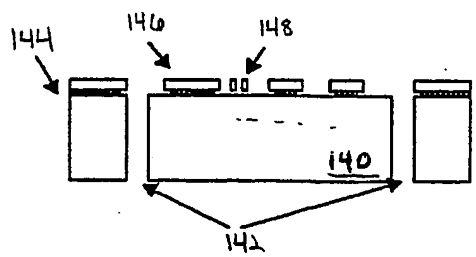


Fig. 9

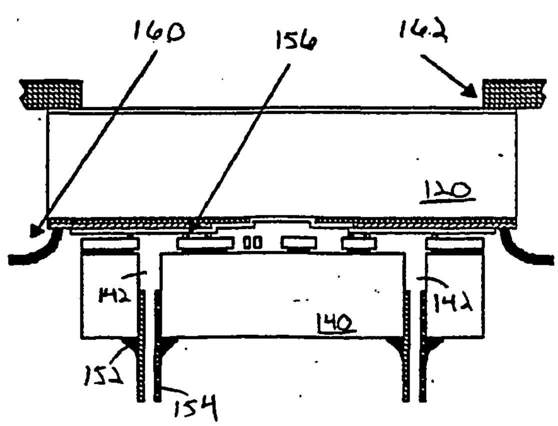


Fig. 10

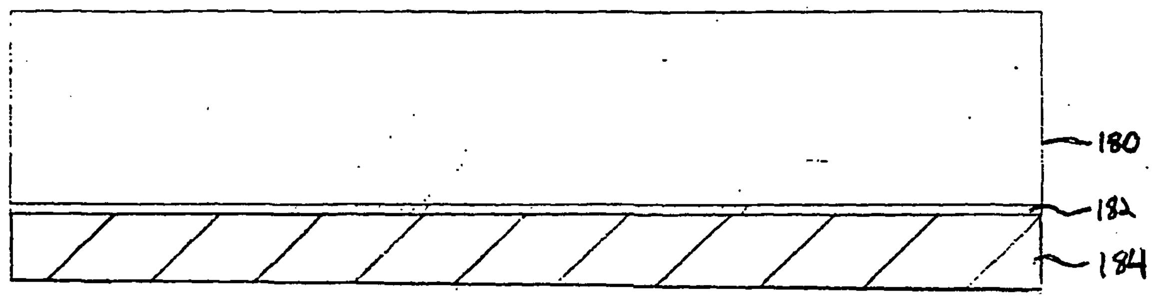


Fig. 11A

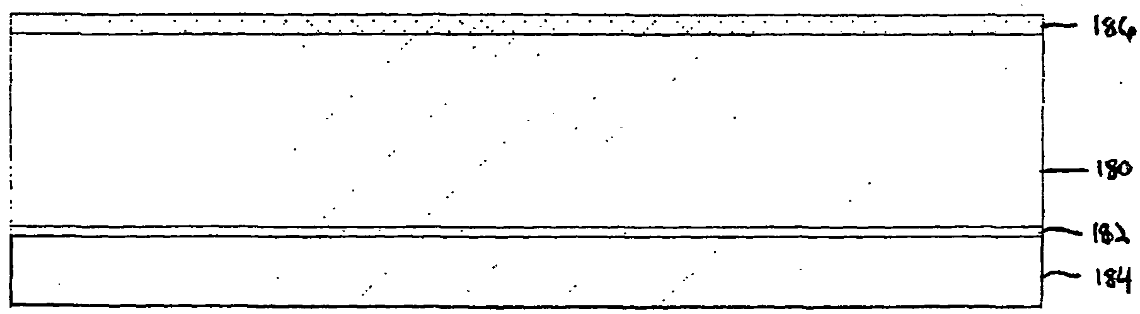


Fig. 11B

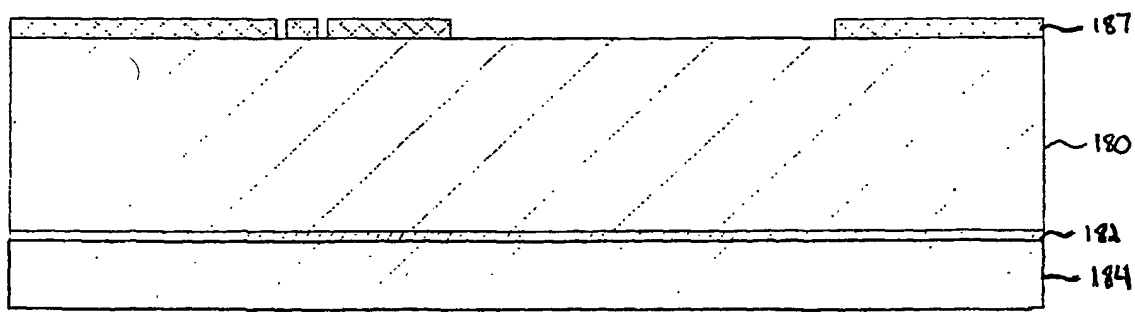


Fig. 11C

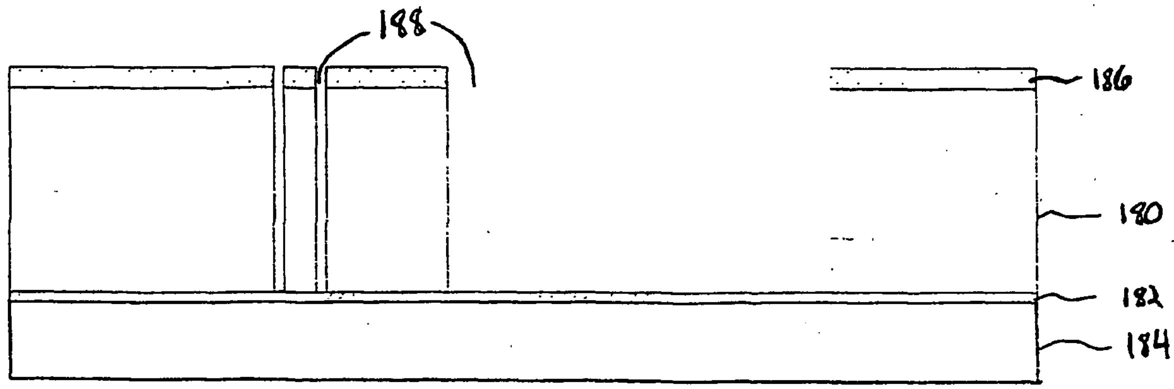


Fig. 11D

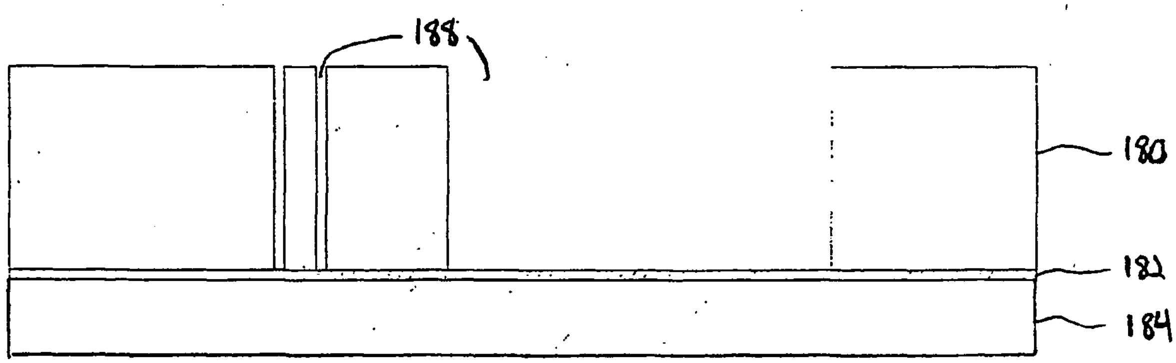


Fig. 11E

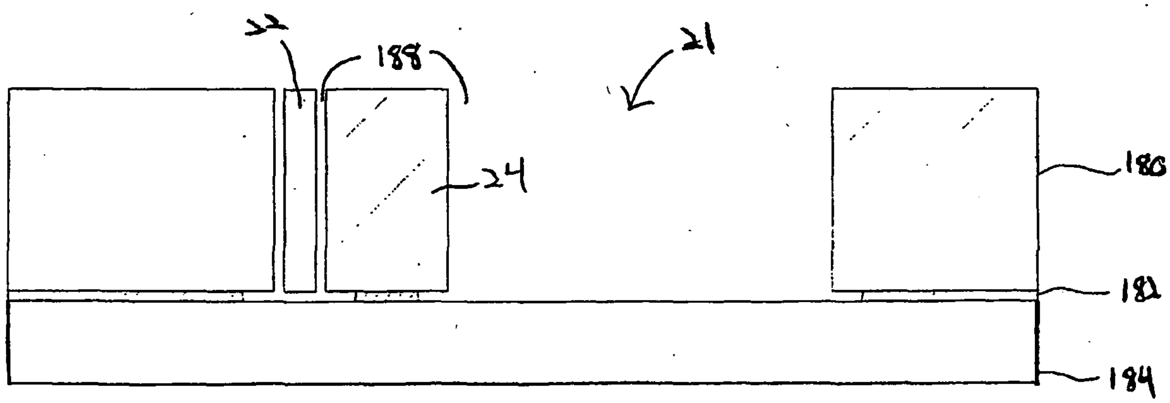


Fig. 11F

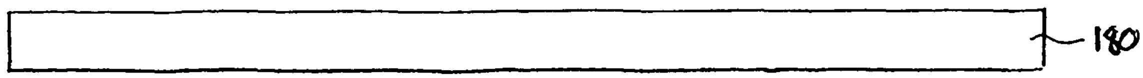


Fig. 12A

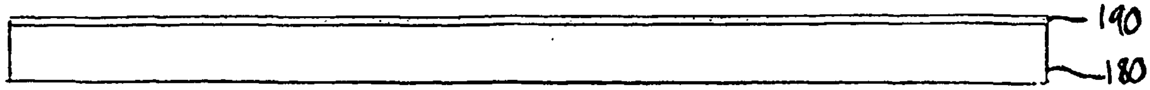


Fig. 12B

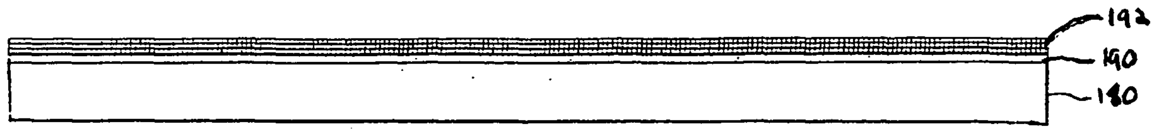


Fig. 12C

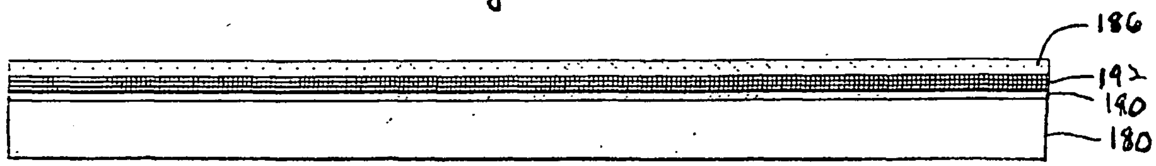


Fig. 12D

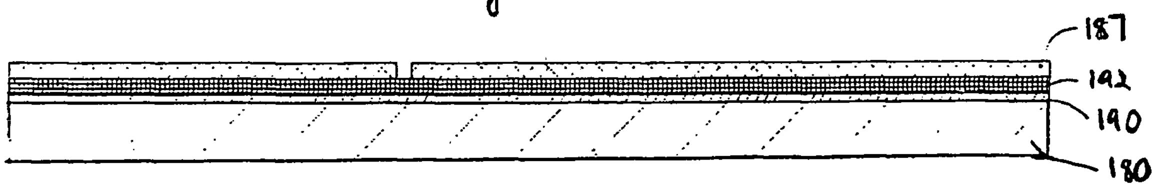


Fig. 12E

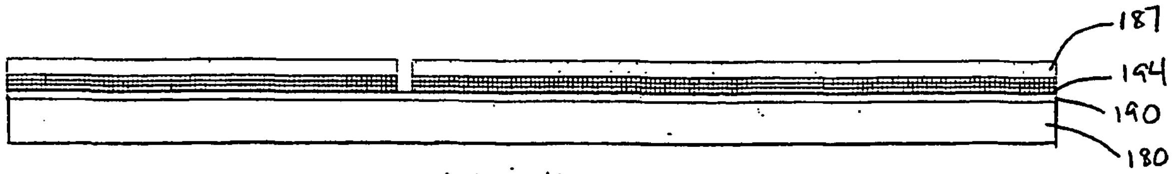


Fig. 12F

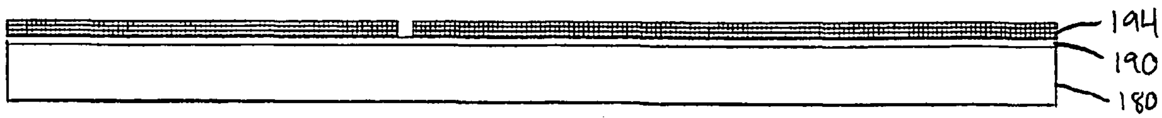


Fig. 12G

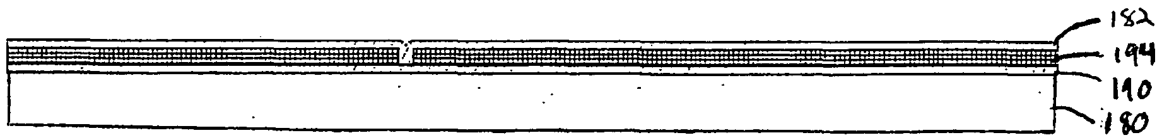


Fig. 12H

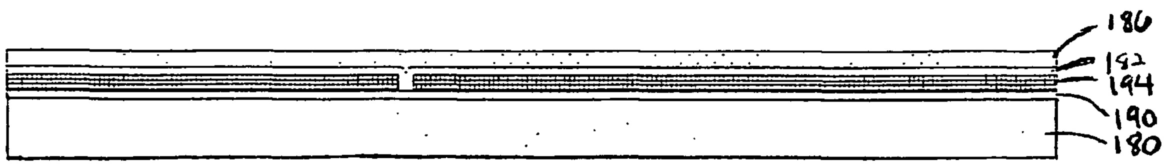


Fig. 12I

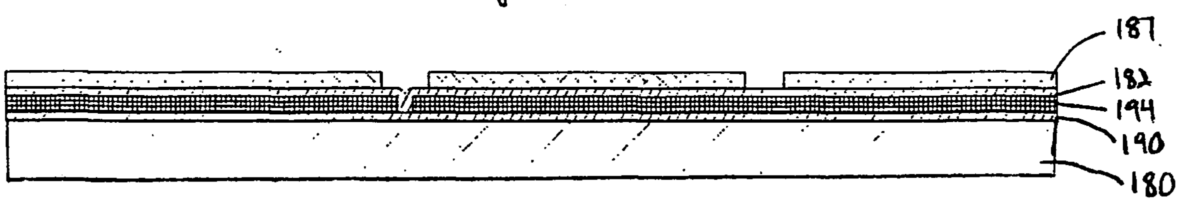


Fig. 12J

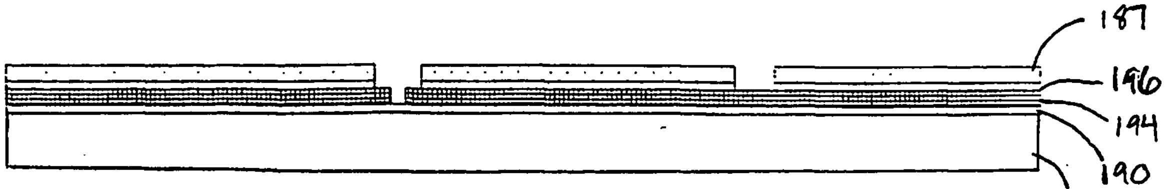


Fig. 12K

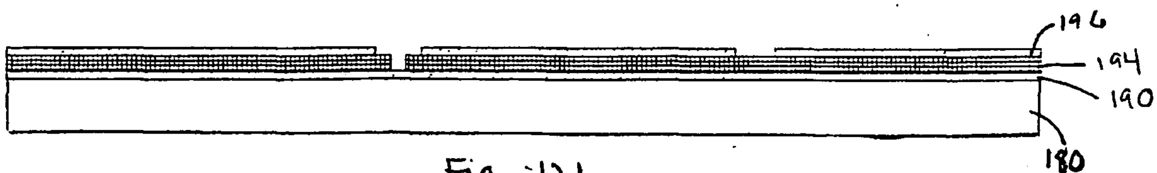


Fig. 12L

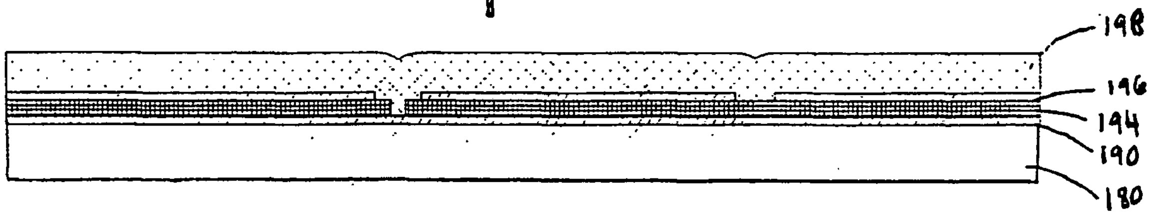


Fig. 12M

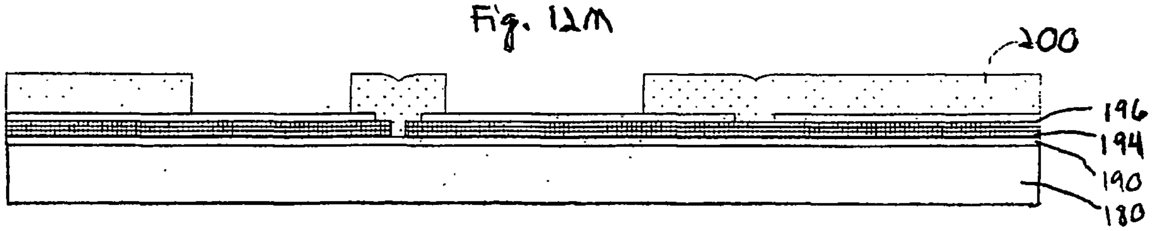


Fig. 12N

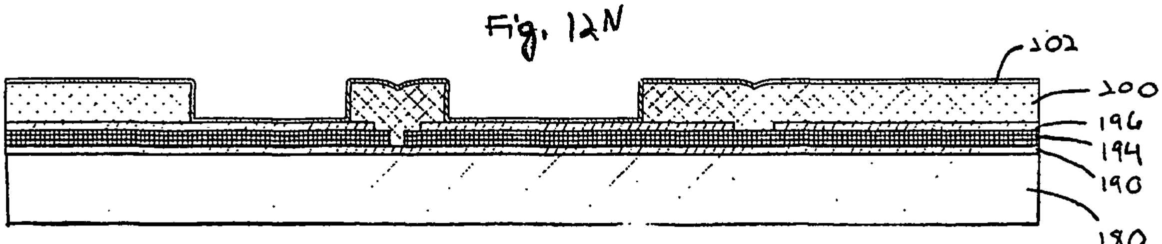


Fig. 12O

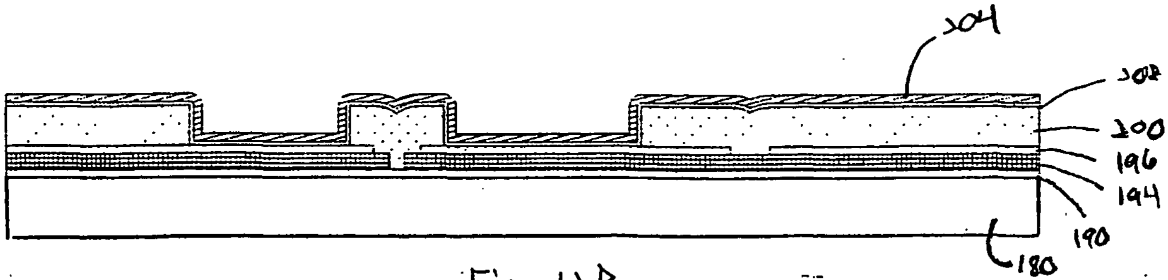


Fig. 12P

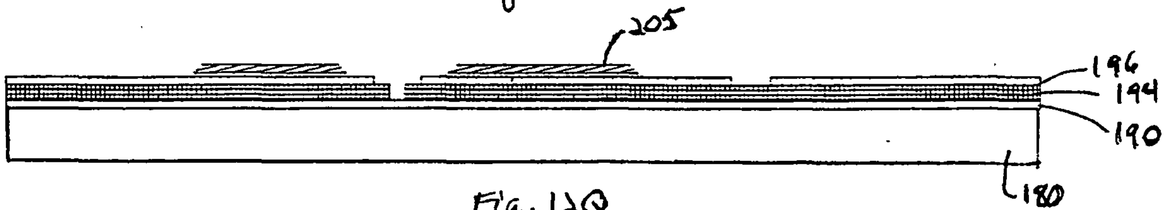


Fig. 12Q

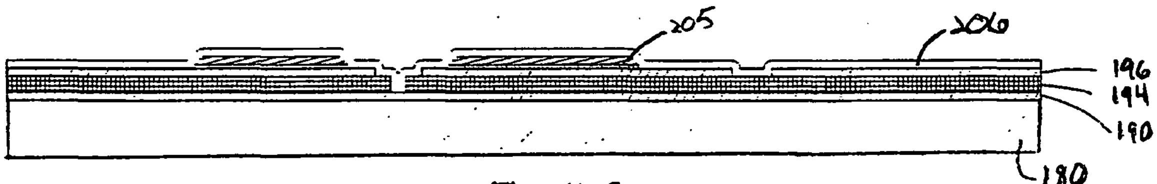


Fig. 12R

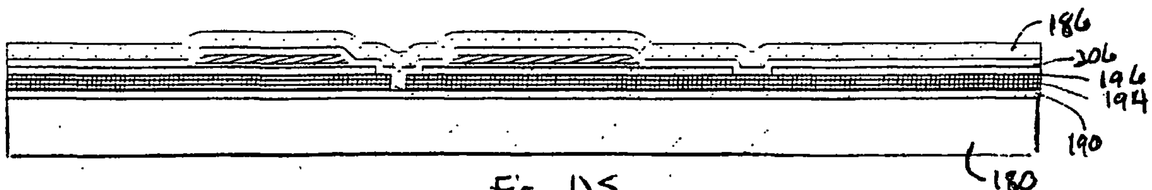


Fig. 12S

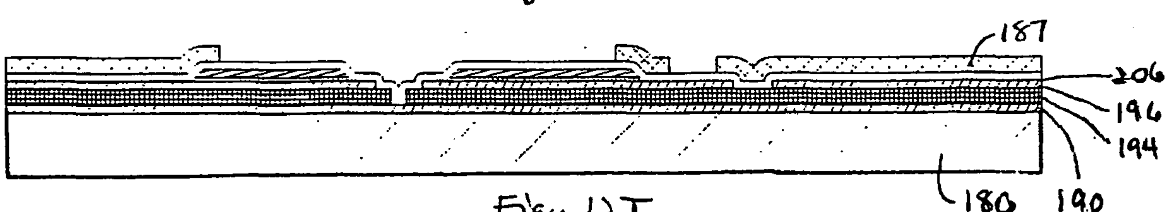


Fig. 12T

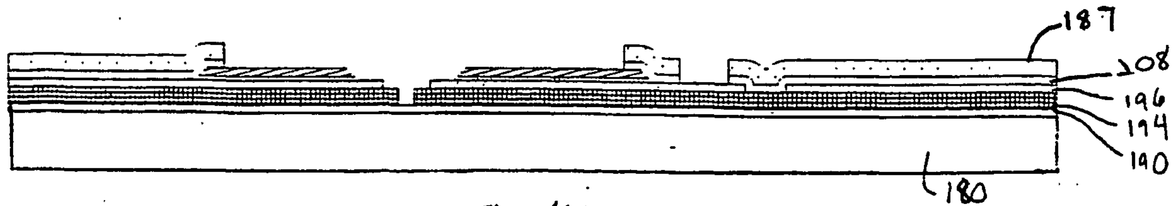
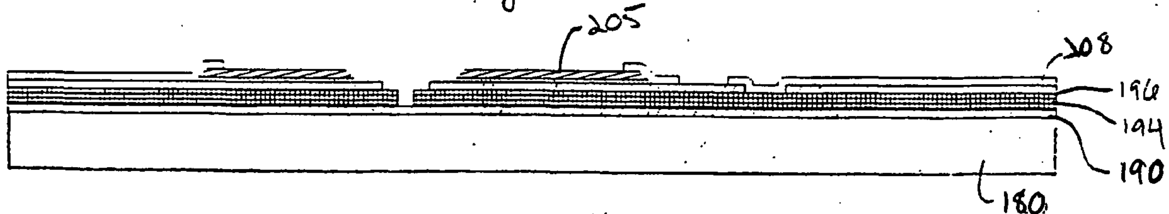


Fig. 12U



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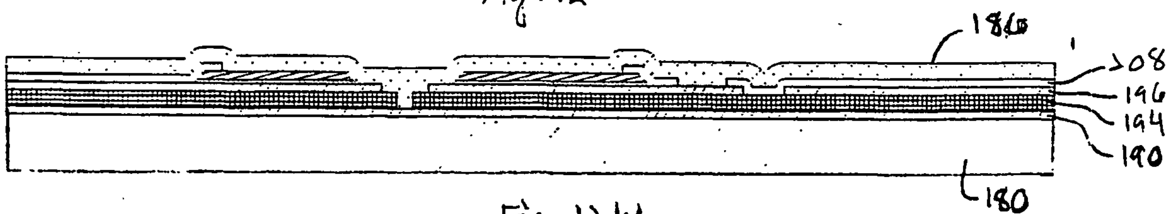


Fig. 12W

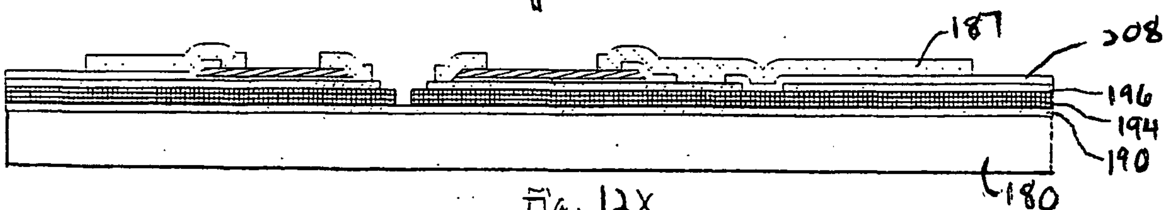


Fig. 12X

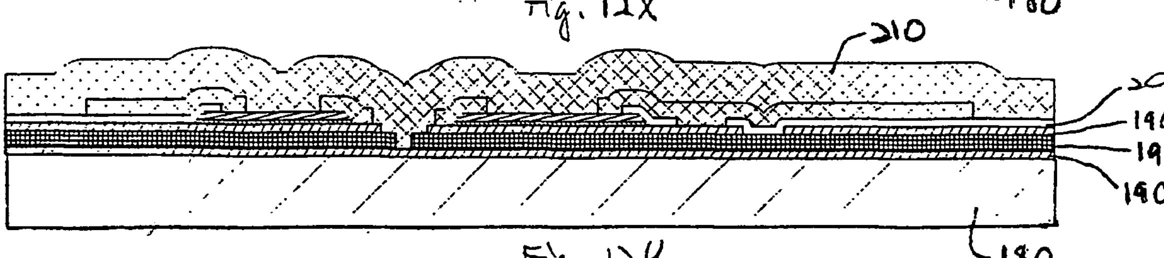


Fig. 12Y

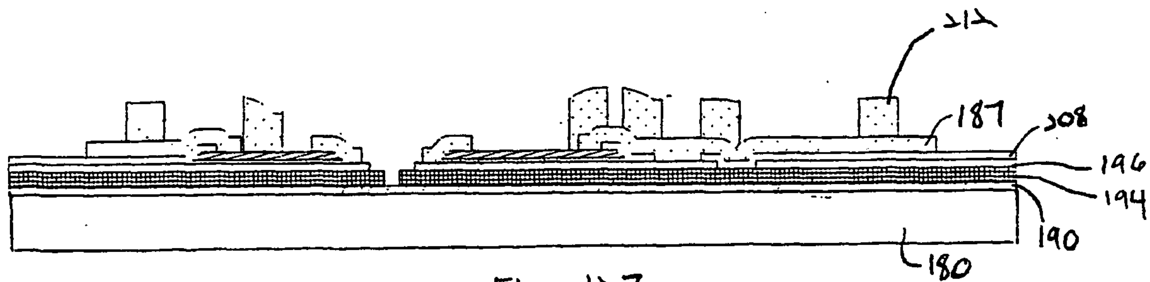


Fig. 12Z

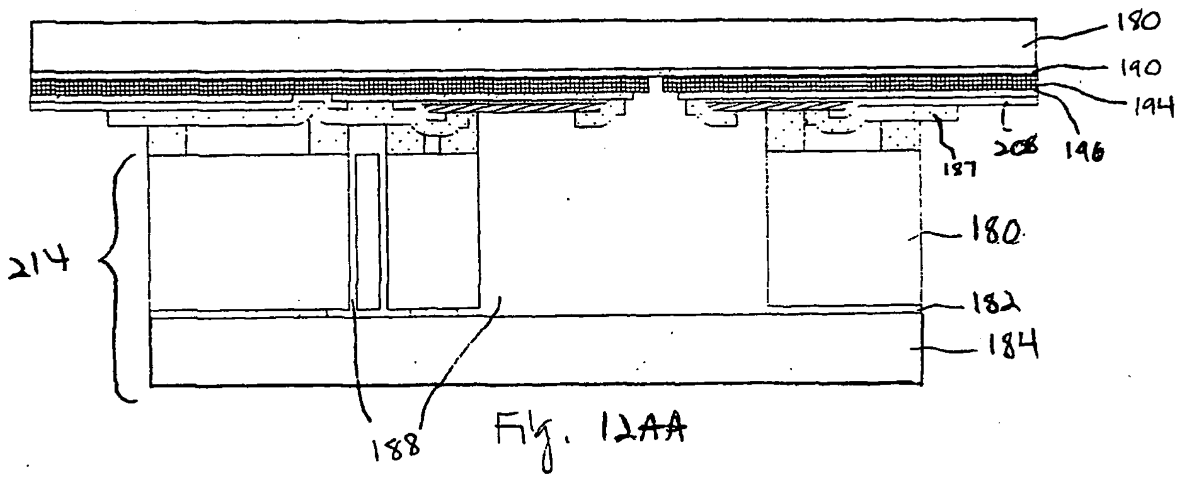


Fig. 12AA

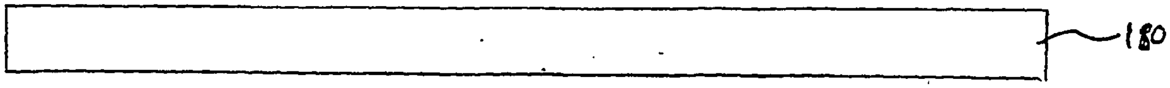


Fig. 13A

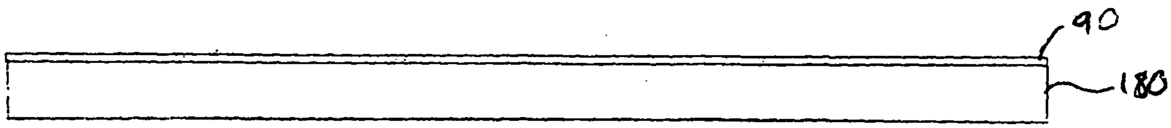


Fig. 13B

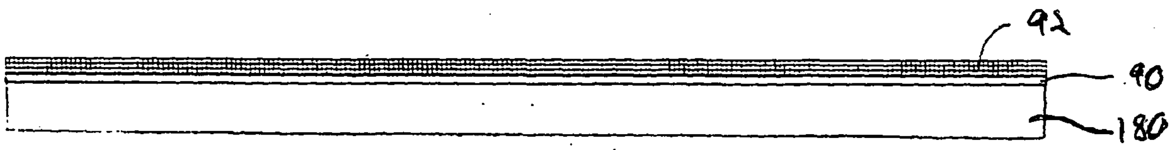


Fig. 13C

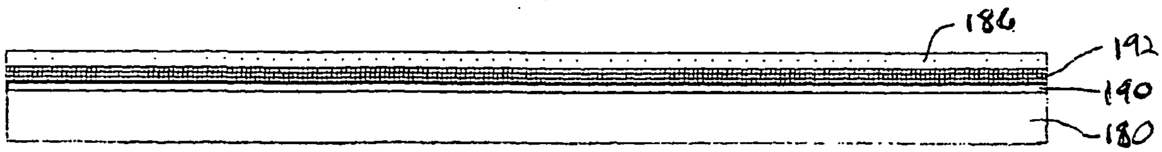


Fig. 13D

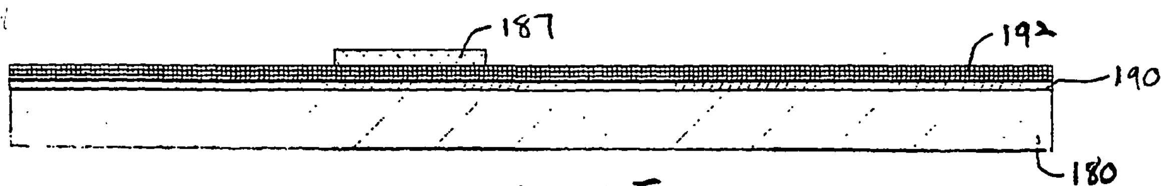


Fig. 13E

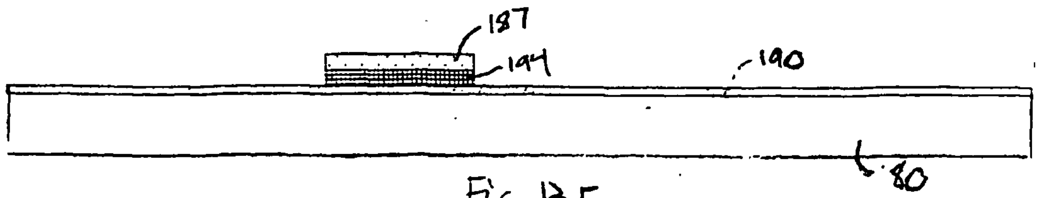


Fig. 13F

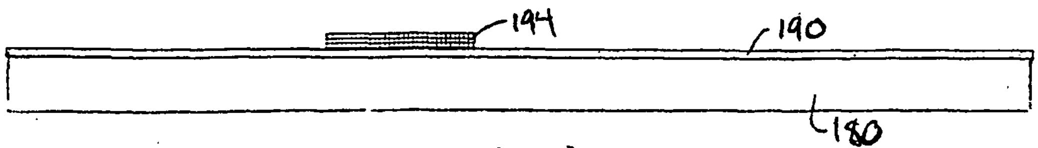


Fig. 13G

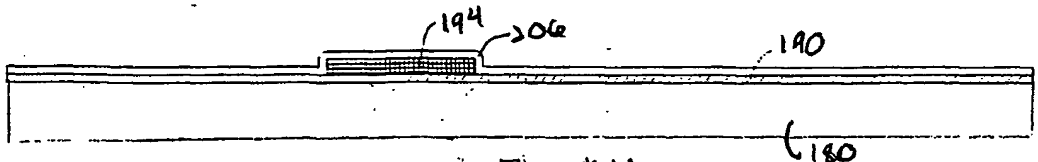


Fig. 13H

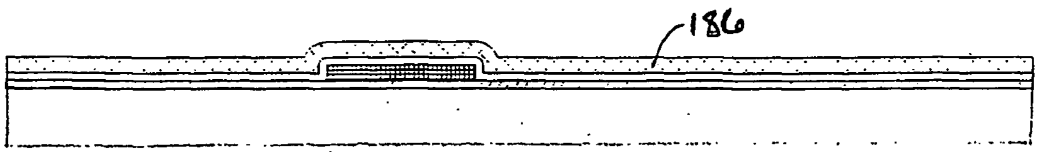


Fig. 13I

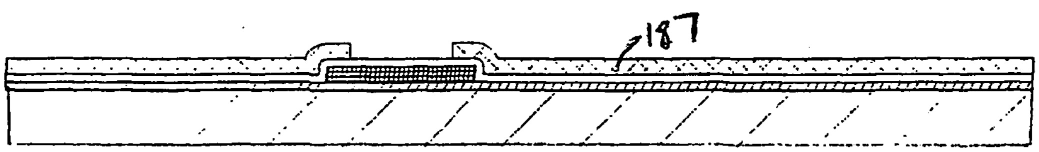


Fig. 13J

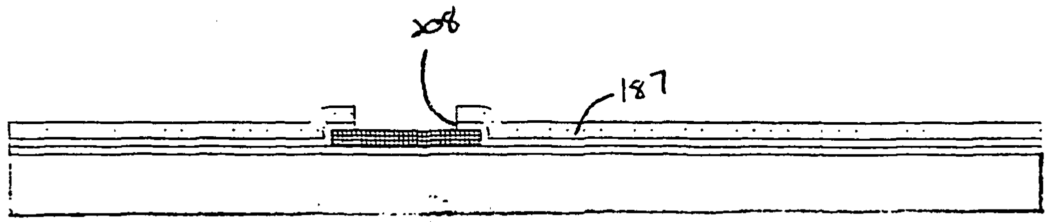
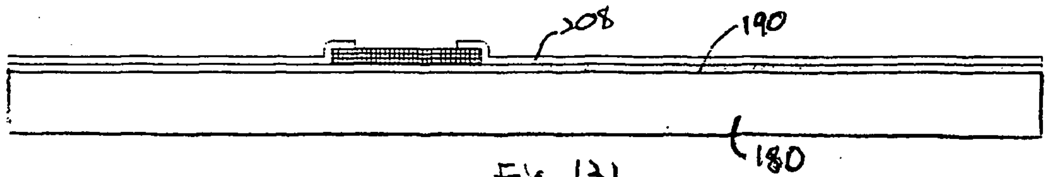


Fig. 13K



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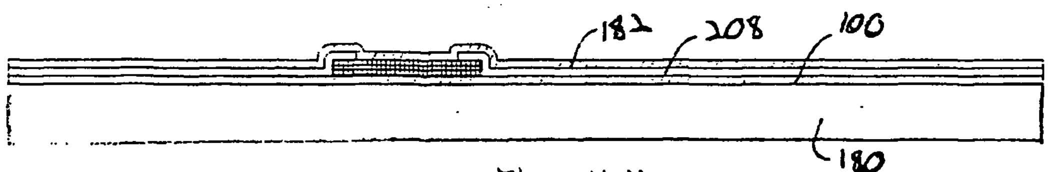

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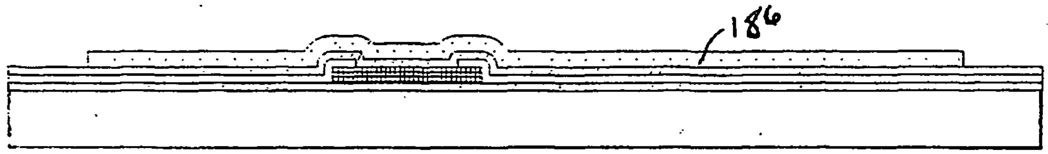
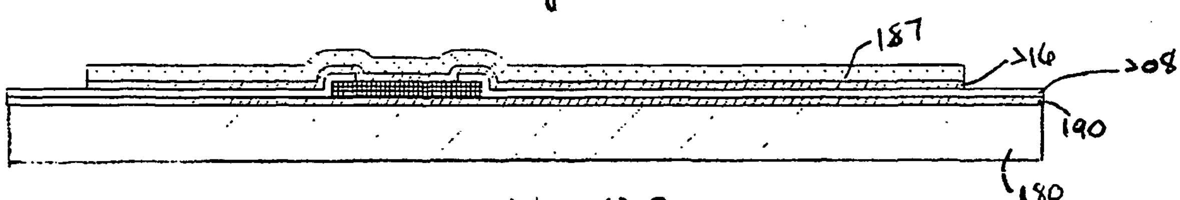


Fig. 13N



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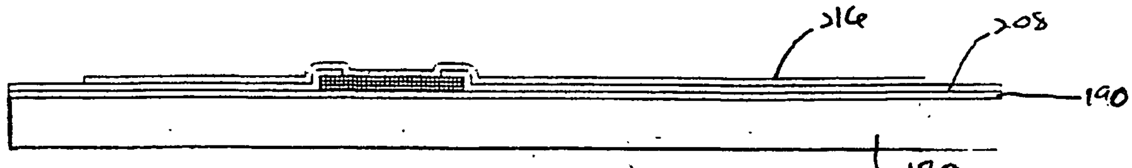

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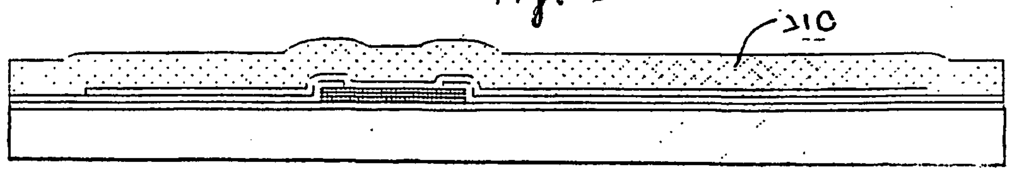


Fig. 13Q

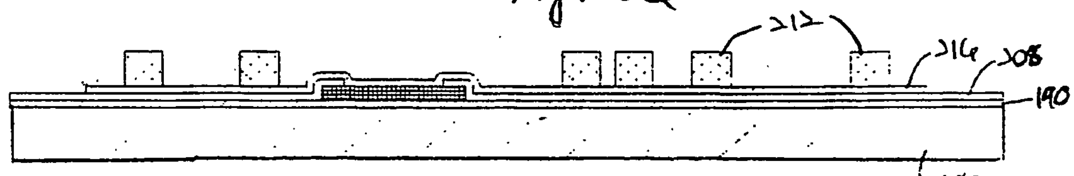


Fig. 13R

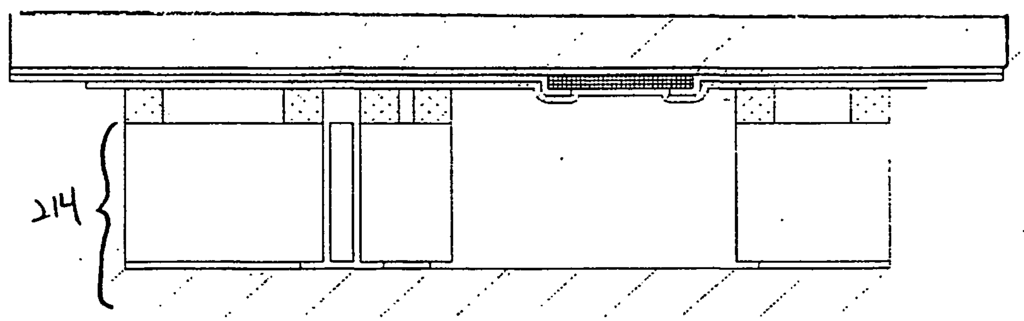


Fig. 13S

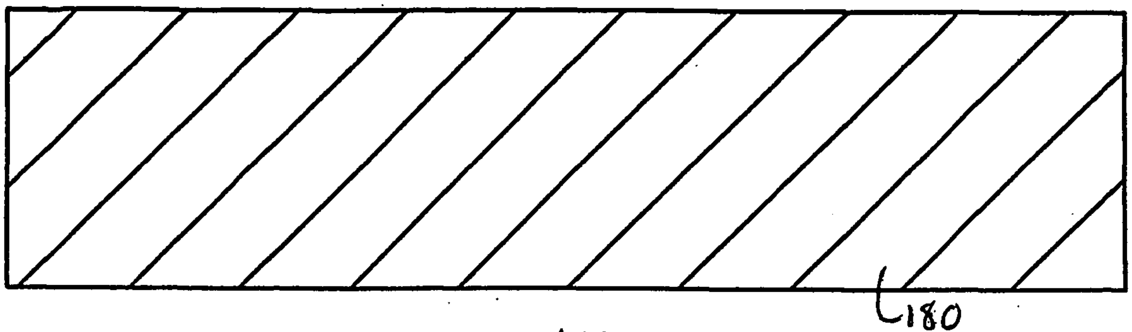


Fig. 14A

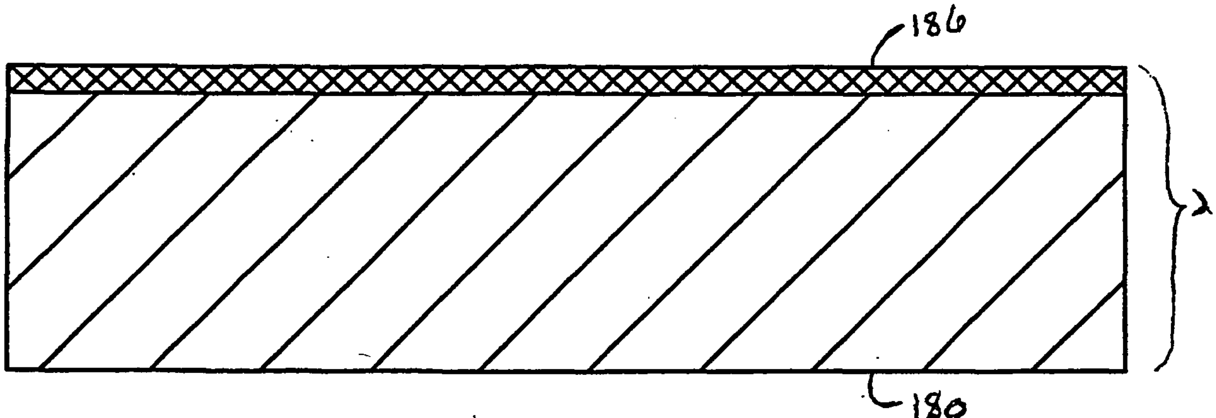


Fig. 14B

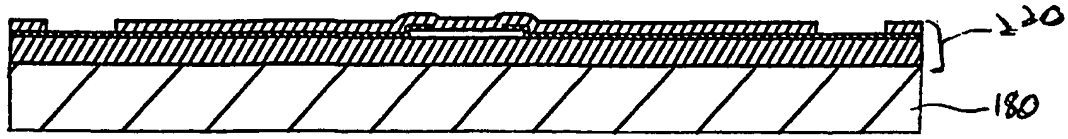


Fig. 14C

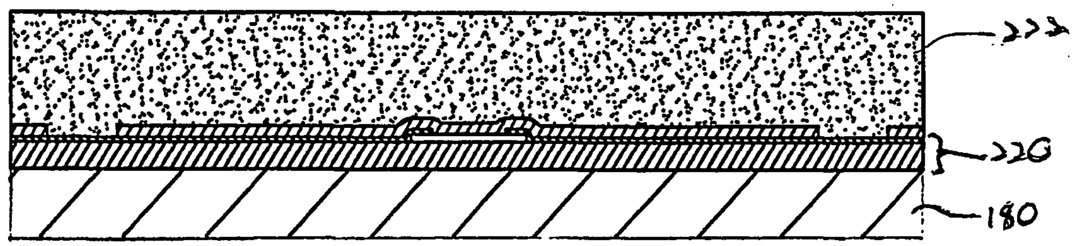


Fig. 14D

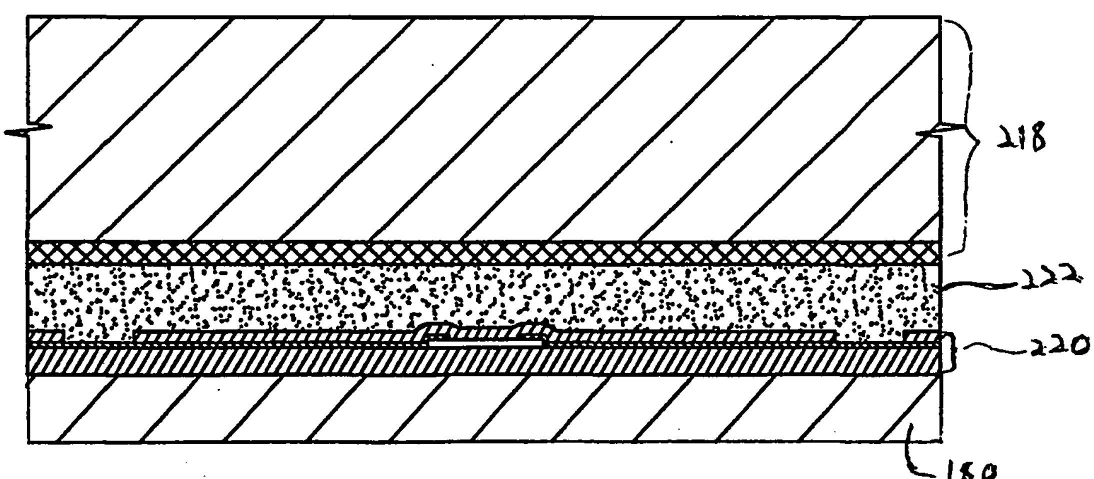


Fig. 14E

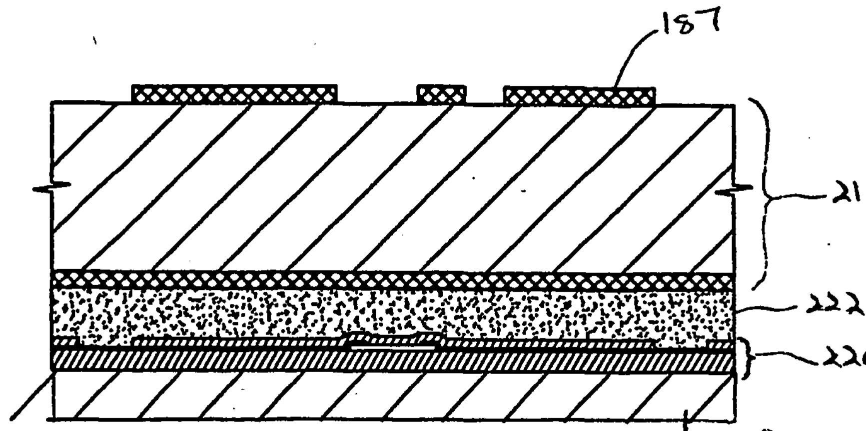


Fig. 14F

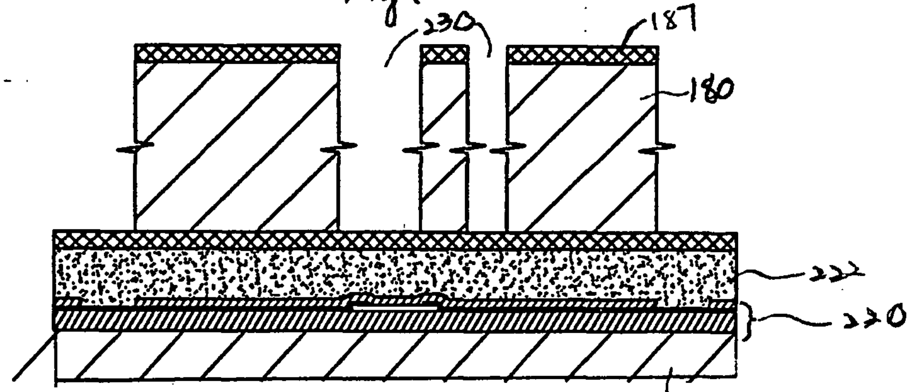


Fig. 14G

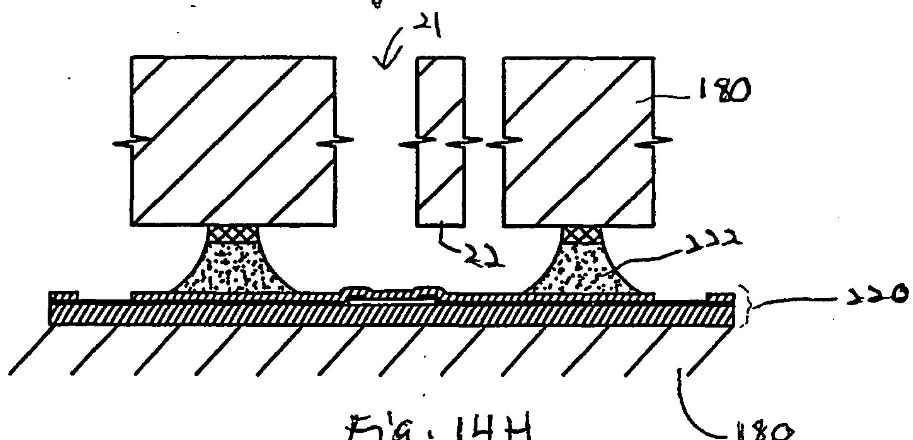
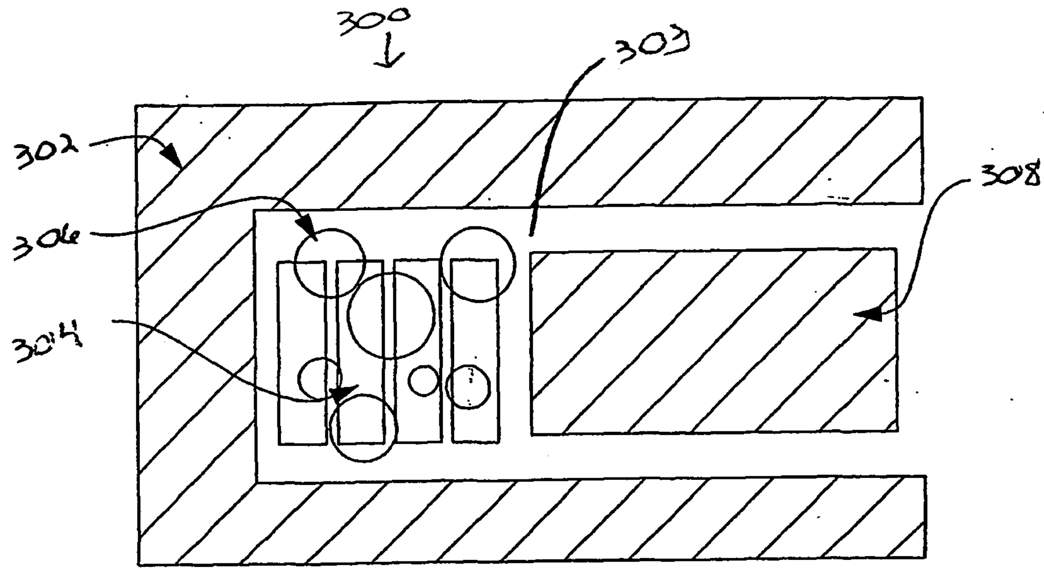


Fig. 14H



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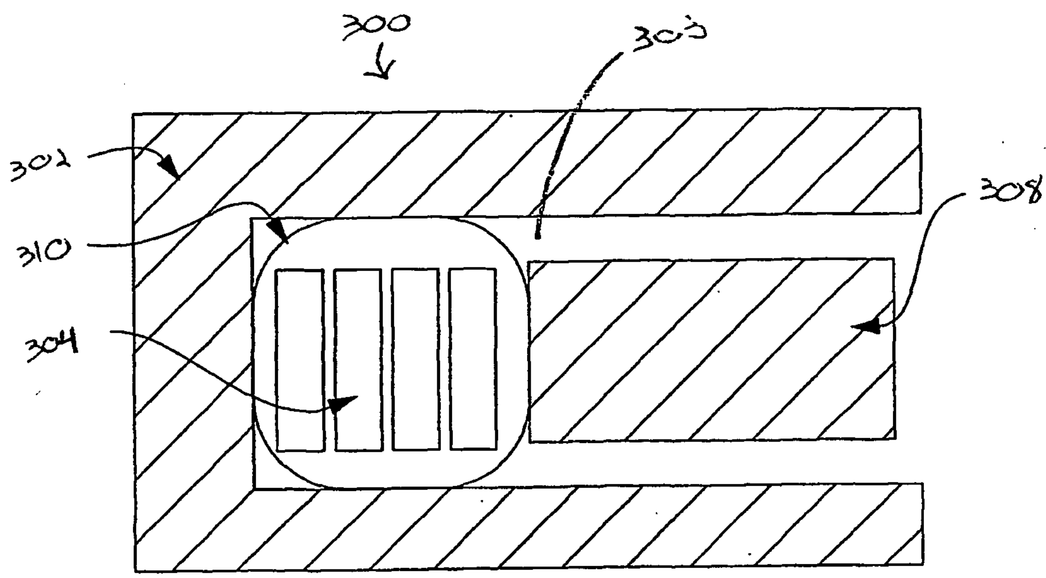
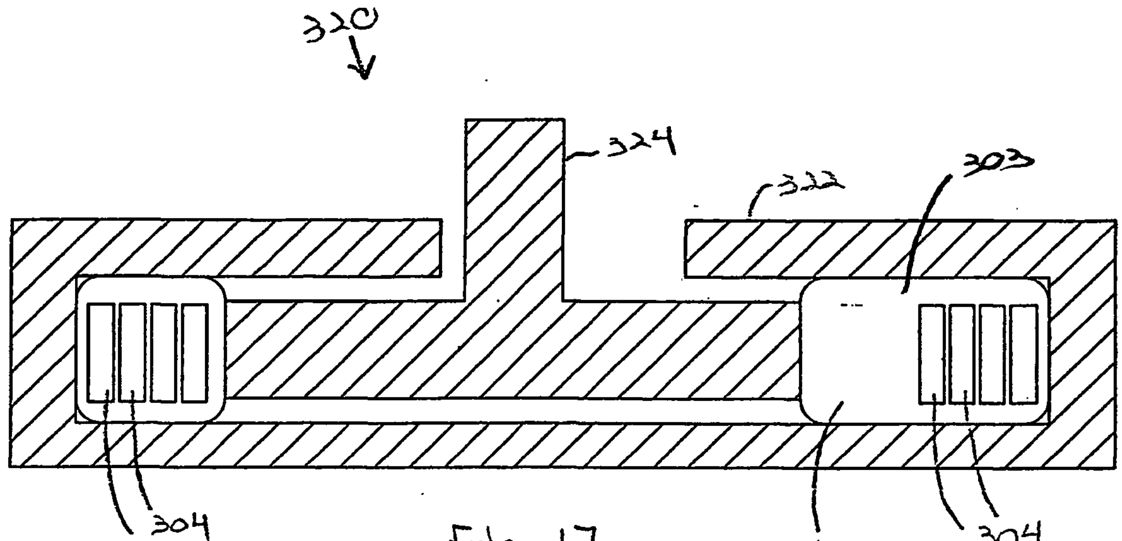


Fig. 16



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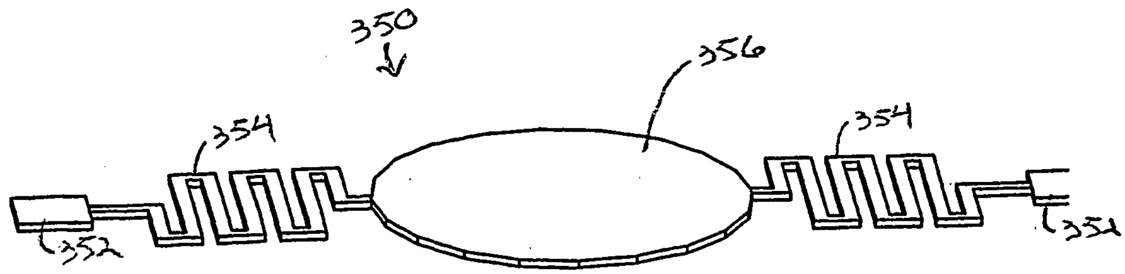

Fig. 18a

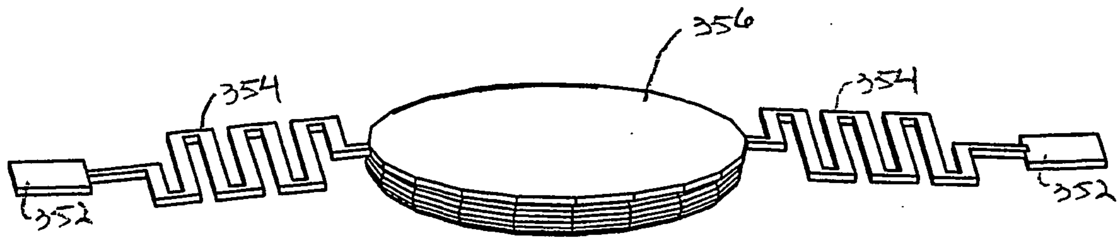

Fig. 18b

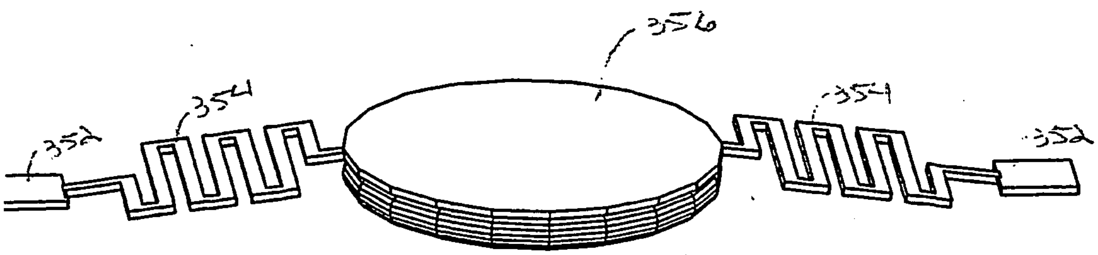

Fig. 18C

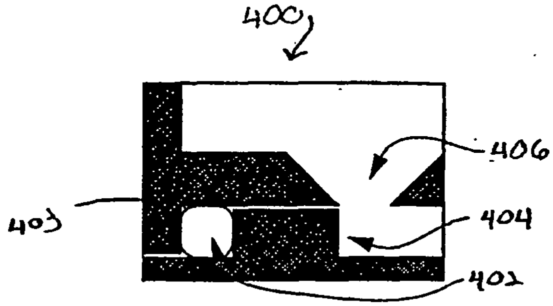

Fig. 19a

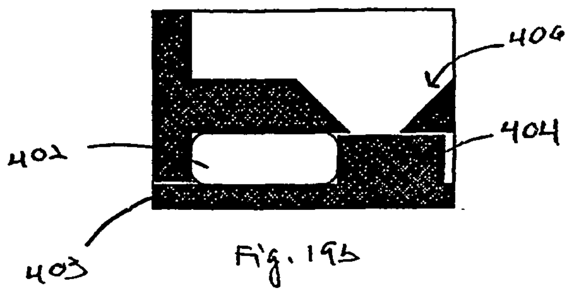

Fig. 19b

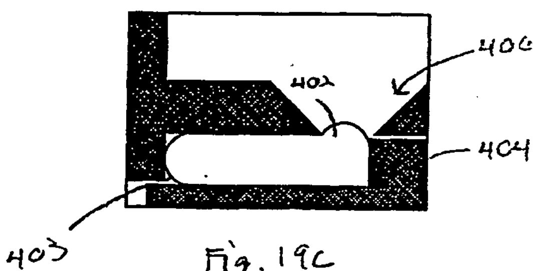

Fig. 19c

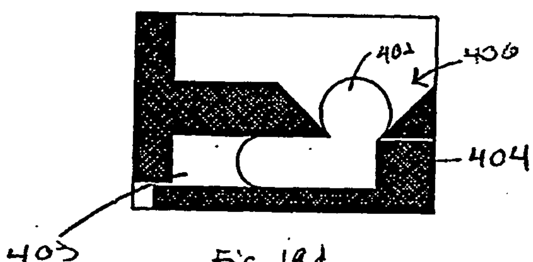

Fig. 19d

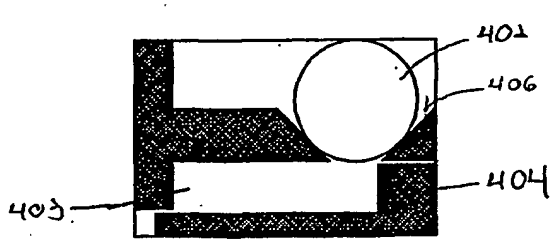

Fig. 19e

INTERNATIONAL SEARCH REPORT	International application No. PCT/US01/17401

A. CLASSIFICATION OF SUBJECT MATTER
IPC(7) :F16K 31/163
US CL :251/11, 129.01; 60/531
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 251/11, 129.01, 129.06; 60/531, 530

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5,671,905 A (HOPKINS, JR.) 30 September 1997, entire document, especially Fig. 4.	1-4,6,9,13-16,18,21
A	US 6,055,899 A (FEIT et al) 02 May 2000, entire document.	1-24

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier document published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
26 JULY 2001	22 AUG 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer KEVIN P. SHAVER Diane Smith f Telephone No. (703) 308-0861